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COLD MILLING OF ASPHALT PAVEMENT AN INVESTIGATION OF AGGREGATE DEGRADATION

Engineering
Materials
Office

COLD MILLING OF ASPHALT PAVEMENT
AN INVESTIGATION OF AGGREGATE DEGRADATION

by

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This report is published without prejudice as to the application of the findings.

COLD MILLING OF ASPHALT PAVEMENT
AN INVESTIGATION OF AGGREGATE DEGRADATION

SUMMARY

Problem: Cold milling equipment used for reclaiming asphalt pavements causes aggregate degradation. Excessive degradation imposes constraints on the types of material suitable for use as virgin aggregate in the recycled asphaltic concrete.

Objectives:

(1) To identify those factors which influenced degradation of aggregates during cold milling of asphalt pavements.

(2) To see if it was possible to predict the amount of aggregate degradation.

Conclusions:

(1) Cold milling of asphalt pavement increases the fines content (-75 μm) of aggregate by about 2 percent (range 0.9 to 3.2 percent). The stone content (+ 4.75 mm) is reduced by about 6 percent (range 3.8 - 8.1 percent).

(2) The following variables were found to significantly influence aggregate degradation:

Machine type
Pavement temperature
Milling machine speed.

Other factors may have an influence.

(3) It is not practical to predict aggregate degradation because of the significant influence of pavement temperature and milling machine speed on degradation.

Recommendation:

We recommend that this study be continued in order to obtain more information about aggregate degradation during cold milling. Two contracts should be studied in detail.

ACKNOWLEDGEMENTS

The information used to write this report was collected by a large number of people. This was a group effort in the widest sense. Technicians from the MTC Downsview laboratory, MTC project supervisors and inspectors and contractor personnel all contributed toward the collection of data. We would like to specifically thank the following people: Bill Arnold and Ted Arscott of Roto-Mill Services, Faizul Bacchus, Eric Betts, Gary Gage, John Graham, Alexander Leslie and John Nadal, of M.T.C. for collecting samples, providing advice and laboratory testing.

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INTRODUCTION

Prior to recycling of asphalt pavement it must be removed from the highway. There are a number of different techniques for recovering the old pavement: ripping the whole pavement and crushing at a central plant, pulverizing in place, hot milling and cold milling. This report is concerned exclusively with cold milling.

A short case history illustrates the reason for this study. A recent contract was designed so that a crushed gravel passing the 16.0 mm sieve would be used as the virgin aggregate. This material, which included the sand fraction, would be blended with reclaimed asphalt pavement and some new asphalt cement to produce a recycled mix. The final mix was of a 70:30 (reclaimed: virgin) ratio. The old asphalt pavement had been placed in the early 1950's. It is reported to have been made with about 32 percent crushed limestone as the coarse aggregate and 68 percent limestone screenings and blending sand and contained about 4 percent fines. Since original construction, a certain amount of patching had taken place. The results of tests on six full depth cores from the pavement showed it contained about 38 percent stone and 5 percent fines (pass 75 µm). The top 50 mm of asphalt pavement was removed using a 3.6 m wide cold milling machine. Cold milling machines have a horizontal rotating screw with tungsten carbide tipped milling teeth set into it (Appendix 3, Figures 29 and 30). The grinding action of these teeth on the pavement breaks the pavement and in doing so increases the fines content and reduces the stone content of the reclaimed material. The milled material contained an average of 26 percent stone (range 22.5 - 37.6). There was an average of 9.7 percent fines (range 6.6 - 11.6). The low amount of stone and the high fines content of the reclaimed material made the design of a satisfactory mix using the proposed granular material at the desired recycling ratio, impossible. As a result, the granular material originally specified could not be used. A satisfactory mix was finally obtained by substituting a blend of 4 parts of coarse aggregate and 1 part of clean, fine blending sand for the virgin granular material in the recycled mix. This increased the cost of the contract substantially.

INTRODUCTION cont'd

The generation of fines has been recognized as a major problem in the use of cold milling equipment for reclaiming asphalt pavements (Servas,1980). The quantity of fines imposes restrictions on the ratio of reclaimed pavement that can be used, due to the need to design sufficient voids into the mix (TAM et al, 1981). The quantity of fines in reclaimed material can often be greater than 8 percent (Servas,1980).

The problem with generation of fines experienced on the recycling project described above was not an isolated instance. As a result of this experience and others, where separate virgin stone and sand had to be used (in place of the desired granular material), at an extra and unexpected cost, a short investigation of degradation caused by cold milling was conducted. In 1980, four contracts were investigated. In 1981 an additional five contracts were investigated in greater detail.

The objective of this investigation was to see if it was possible to predict the aggregate gradation of the reclaimed, milled pavement. If degradation can be predicted it would enable us to know before contract tendering whether or not a crushed gravel could be used as the virgin aggregate and still obtain satisfactory recycled asphalt mix properties.

Briefly, the experimental approach was as follows: An undisturbed sample of asphaltic concrete was taken from the pavement some distance in front of the milling equipment. When the milling machine had reached the same location as the pavement sample, a sample of the milled pavement was taken from the discharge chute of the machine. In the laboratory, duplicate samples of the pavement and milled material were subjected to the asphalt extraction test and the gradings of the aggregate compared. Using this technique it was possible to make a comparison of decrease in stone content and increase in fines caused by the milling process. This approach also allowed us to investigate the effects of pavement temperature, moisture contents, equipment type, aggregate type, and milling teeth condition on the amount and nature of degradation of individual samples.

SAMPLE COLLECTION

In 1980, pavement and milled pavement samples were taken. In the expanded investigation in 1981 more data was collected such as pavement temperature and moisture content. The method of taking samples and recording field data is described below.

Pavement Sample:

At a suitable distance ahead of the milling operation, a sample of pavement about .25 x .25 m was sawn and removed from the centre of the wheel track using a portable saw. The thickness of pavement sampled was equal to the depth of milling. Locations and lane directions were recorded.

Milled Sample:

A sample of the milled product was taken from the same location as the pavement sample. When the milling machine had reached the pavement sample location, a sample of about 25 kg was taken from the discharge chute of the machine. This was done by putting a shovel in the flow of material. In cases where the flow of material was too great it was sometimes possible to get the operator to adjust the rate of discharge from the machine. This allowed the collection of a more representative sample.

Moisture Content Sample:

Samples of the milled pavement for moisture content determination were taken at the same location as the pavement samples. 'Triple tight', one gallon cans were filled to 2/3 capacity, sealed and labeled.

Pavement Temperature:

Pavement temperature measurements were taken at the time of sample collection near the pavement sample location. A tempered steel spike was hammered into the pavement to a depth of about 70 mm and removed. A thermometer capable of reading to 0.5°C was inserted. Care was taken to shade the thermometer from direct sunlight before and during temperature measurement.

SAMPLE COLLECTION cont'd

Milled Pavement Temperature:

Immediately following collection of the milled pavement sample a thermometer was inserted about 70 mm into the material and the temperature recorded.

Miller Speed:

Three measurements of uninterrupted progress at the pavement sample locations were averaged and recorded as feet per minute.

Condition of Milling Teeth:

Periodic changes of cutting teeth are necessary due to abrasive wear. A note of when the last change in teeth took place and how many hours of production since the change gave hours of wear.

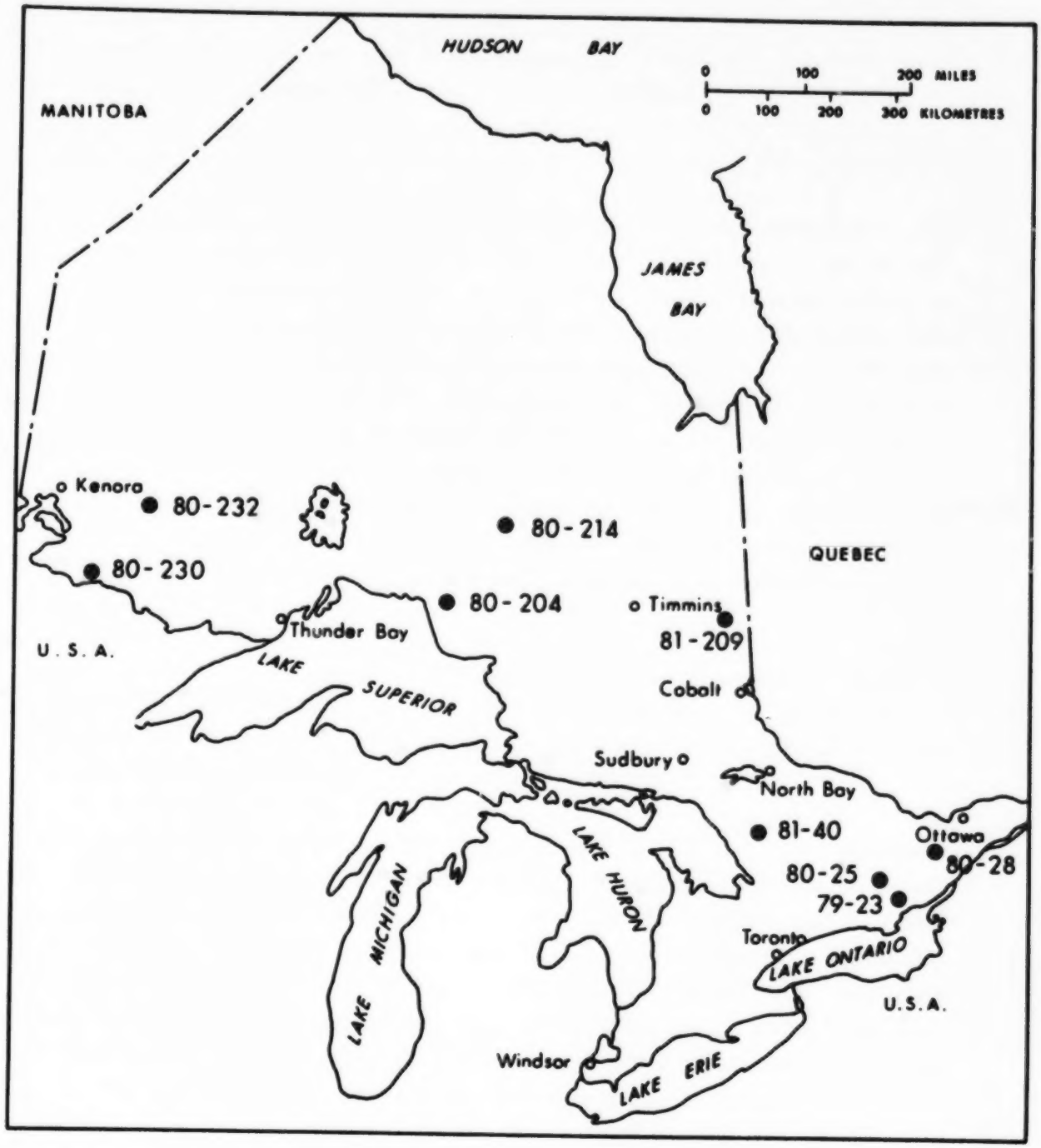

Figure 1. Location of 1980 and 1981 Recycling Contracts involving use of cold milling equipment studied in this investigation.

LABORATORY TESTING

The samples collected were tested in the MTC Downsview Testing Laboratory. All testing was done at the same time by the same technicians. This was done to reduce, as far as possible, testing variation due to operator and within laboratory differences.

Pavement Samples:

The slabs of pavement were brushed to remove dirt and dust. The edges were broken off by hand to remove aggregate particles cut in half by sawing. Inclusion of these particles would have introduced errors in measuring the proportion of coarse and fine aggregate. The asphalt contents and particle size distribution were determined following MTC Test Method LS-282. It is worth noting that all extractions were done in duplicate, sometimes in triplicate and the mean of the individual results taken as the final reported grading. An example of individual and mean results is given in Appendix 1, Table 1. It can be seen that the individual results on each sample are in agreement with each other. Thus, reported differences in grading between pavement and milled samples are significant.

The extracted aggregates were petrographically examined to determine the major rock types occuring in the coarse aggregate. The method outlined in the MTC procedure for petrographic analysis was followed (MTC Test Method LS-609).

A fineness modulus (F.M.) was calculated for the total aggregate gradation. The method described in part 8 of the MTC construction manual was followed. This differed from the conventional calculation, in that the coarse aggregate fraction was also included in the calculation. Fineness modulus was calculated to give a rough indication of aggregate gradation. When compared with the fineness modulus of the milled pavement samples, the modulus gave another measure of breakdown in addition to the change in stone content and change in fines content.

A summary of test results is given in Appendix 1, Table 6.

LABORATORY TESTING cont'd

Milled Samples:

The bulk samples (25 kg) were reduced by splitting into duplicate samples of about 1000 g each. Asphalt content, particle size distribution, major rock type and fineness modulus were determined following the procedures used for the pavement samples. A summary of results is presented in Appendix 1, Table 6.

Moisture Content:

The moisture contents of the milled pavement samples were determined by following the standard method for laboratory determination of moisture content of soil (MTC Test Method LS-701).

Modified Impact Test:

In an attempt to obtain quantitative data on the strength of the aggregates in the pavement, an impact test was used. The aggregate impact value was determined for aggregate extracted from the pavement samples collected in 1981. The method described in B.S. 812 (1975) was followed except for a modification in sample grading.

The British Standard specifies two samples of about 500g passing a 14.0 mm, retained 10.0 mm sieve. Because of limited amounts of material, a single sample of 200g of 13.2 - 9.5 mm and 150g of 9.5 - 6.7 mm aggregate was tested. Following 15 impact blows the material was passed over a 2.36 mm sieve and the percent loss calculated. The results are reported in Appendix 1, table 7.

There is a significant correlation between the aggregate impact test and Los Angeles abrasion test ($r = 0.80$ for 100 samples) reported by Hudec (1981).

RESULTS AND DISCUSSION

The test results are presented in Appendix 1. Grading charts showing changes in grading caused by milling are shown in Appendix 2.

AVERAGE CHANGE IN GRADING:

Table 1 shows the mean and range of changes in grading for eight of the contracts investigated. The increase in fines content of between 0.9 and 3.2 percent agrees well with the observations of others. In Michigan, Welke (1980 and 81) found cold milling increased fines content by about 3 percent. Grant and Scherocman (1981) found that the Barber-Greene milling machine increased the fines content by 2 to 3 percent.

It should be noted that the figures given in Table 1 only apply to CMI and Barber-Greene equipment.

	Mean	Range
Change in percent retained on 4.75 mm sieve	-5.63	-3.8 to -8.1
Change in percent passing 75 µm sieve	1.86	0.9 to 3.2
Change in Fineness Modulus	-0.377	-0.22 to -0.50

Table 1 Summary of change in gradation due to milling for 8 contracts investigated in 1980 and 81. Contract 80-204 excluded due to suspect results. (Data from Appendix 1, Table 8).

EFFECT OF DIFFERENT MACHINES:

On Contract 80-28 a Sakai milling machine was used. This machine produced milled asphalt with a finer grading than the CMI machine used on the same contract. The Sakai machine increased fines in the milled pavement by about 3.1 percent. The CMI machine increased fines by about 2.5 percent at the same location (See Table 2). The Sakai machine had

RESULTS AND DISCUSSION cont'd

just been fitted with new teeth at the time the samples were taken. As the teeth wear down, they become less efficient leading to a further reduction in stone content. Field extraction data showed that the Sakai machine generally produced a milled product with about 20 percent stone and 10 percent fines. The CMI machine generally gave a product with about 30 percent stone and 8 percent fines. (Evers, 1981)

Clearly, the type of equipment used for milling had an influence on the extracted aggregate grading of the reclaimed pavement.

	Original Pavement	MILLED PAVEMENT CMI Machine	SAKAI Machine
Percent retained on 4.75 mm sieve	35 (approx.)	29.7	20.0
Percent passing 75 µm sieve	5 (approx.)	8.0	10.2

Table 2 Comparison of aggregate degradation from different milling machines on the same section of asphalt pavement.

EFFECT OF MOISTURE:

All equipment used for cold milling is designed to add water to the pavement at the time of milling. This is done to reduce dust and to cool the teeth which otherwise would get extremely hot. Hot teeth 'burn' and deteriorate more rapidly. The wear of the teeth and the need to replace them is a major cost of milling. As can be seen from Appendix 1, Table 6 the moisture content of milled pavement varied between 0.6 and 3 percent. From the limited data available it was not possible to correlate aggregate degradation with moisture content.

Rainfall prior to milling has an influence on aggregate degradation. Sample No. 3 on contract 80-230 was taken following a shower of rain. Table 6 in Appendix 1 and figure 19, Appendix 2, show that there was a very small decrease in stone content and a small increase in fines content when this wet pavement was milled. Water entered the asphalt

RESULTS AND DISCUSSION cont'd

pavement, possibly weakening the material. Milling probably broke the pavement at the asphalt/aggregate bond rather than through the aggregate particles. This may account for the substantially reduced amount of degradation.

In view of the experience on Contract 80-230 it may be worth while investigating in greater detail the effects of wetting the pavement some time prior to milling. This process should reduce aggregate degradation and substantially reduce the wear of the milling teeth. This would make partial depth milling a more cost effective process than it is at present.

One of M.T.C.'s goals is to reach recycling ratios close to 100 percent (Phang, 1980). Any reduction in aggregate degradation associated with pre-wetting of pavement would make the attainment of 100 percent recycling ratios easier. However, pre-wetting of the pavement would increase the moisture content of the reclaimed material. Removing this moisture from the reclaimed materials is expensive and difficult. Any increase in moisture due to pre-wetting would have to be offset by reducing the amount of water sprayed on the pavement by the milling machine.

PREDICTION OF AGGREGATE DEGRADATION

The data collected was too complex to draw significant conclusions without the aid of statistical analysis. Data reported in Appendix 1, Table 8, was subjected to regression analysis. This data was selected from Table 6 to include as many significant variables as possible.

The results of simple regression analysis are presented in Table 3. The correlation coefficient (r) gives a convenient measure of the extent of the linear relationship between two variables. Generally speaking, the closer the value of the correlation coefficient to 1 or -1 the more likelihood there is that the relationship observed did not occur by chance. A negative correlation coefficient signifies an inverse relationship, or as one variable becomes greater, the other becomes smaller.

RESULTS AND DISCUSSION cont'd

Change in Stone Content:

Change in stone content has a significant correlation ($r = -0.7$) with pavement temperature (See Figure 2). In other words, as pavement temperature increases, the degradation of stone in the milled product decreases. This is to be expected. As the temperature of the asphalt cement increases, the strength of the asphalt/aggregate bond decreases. The milling teeth are then able to break up the pavement without fracturing as many of the coarse aggregate particles.

There is also a significant correlation between change in stone content and change in F.M. ($r = 0.84$). This is a natural result of the close relationship between degradation of aggregate measured on 4.75 mm sieve and overall degradation of aggregate in milled asphalt.

Change in Fines Content:

Change in fines content does not have a significant correlation with either change in stone content ($r= 0.17$) or change in F.M. ($r= 0.23$). This result was unexpected. It had been thought that as degradation increased, as measured by change in stone and F.M., there would be a corresponding increase in the fines content of the milled asphalt.

Change in fines had a significant inverse correlation ($r= -0.77$) with the original fines in the pavement (See figure 3). A smaller amount of fines are generated on milling a pavement with a high original fines content than one with a low original fines content.

It is worth noting that there was no relationship between pavement temperature and the change in fines. In other words the increase in fines caused by milling was not related to pavement temperature.

	PAVEMENT TEMPERATURE	MILLER SPEED	ORIGINAL STONE	ORIGINAL FINES	IMPACT LOSS	DEPTH OF MILLING	CHANGE IN F.M.	CHANGE IN STONE
MILLER SPEED	0.07							
ORIGINAL STONE	-0.63*	0.60*						
ORIGINAL FINES	-0.16	0.15	0.29					
IMPACT LOSS	0.15	-0.38	-0.26	0.39				
DEPTH OF MILLING	-0.01	-0.67**	-0.49	-0.09	0.63*			
CHANGE IN F.M.	-0.50	-0.23	0.36	0.66**	0.14	0.04		
CHANGE IN STONE	-0.70**	-0.22	0.37	0.49	0.13	0.23	0.84***	
CHANGE IN FINES	0.07	-0.52	-0.47	-0.77***	-0.19	0.32	0.23	0.17

TABLE 3 - Correlation coefficients (r) from regression analysis of data presented in Appendix 1, Table 8. n = 11.

* Values significant at 95% level.
** Values significant at 98% level.
*** Values significant at 99% level.

RESULTS AND DISCUSSION cont'd

Miller Speed:

There is some correlation (r= -0.67) between depth of milling and speed of the milling equipment. This is expected. It is surprising that there is not a better correlation. The lack of a highly significant correlation does however coincide with the observation of Scherr (1978). He found that the speed of forward movement of a CMI-750 rotomill was about the same whether 2 inches or 4 inches of pavement was being milled. Grant and Scherocman (1981) found that for Barber-Greene equipment depth of cut did not have an influence on forward speed until a thickness of about 4 inches was exceeded. They concluded that "In general, for cuts up to 4 inches in depth, one planer pass is the most efficient. For depths of cut exceeding 4 inches, two passes with the cold planer will be more efficient."

Pavement Temperature and Miller Speed

On two contracts there was a good relationship between miller speed and pavement temperature (See Figure 5). This relationship is commonly noticed by equipment operators. As the pavement heats up during the day, the asphalt softens and the pavement becomes easier to mill. This relationship does not always occur due to confounding factors such as the pavement moisture and condition of the milling teeth.

Strength of Aggregate

The aggregate impact test (BS 812, 1975) was used to measure the impact strength of the coarse aggregates in the pavement. It can be seen in Table 3 that loss in the impact test did not generally have any significant correlation with other variables. The data studied in this analysis applies to samples collected in 1981. Only igneous and metamorphic rock types were found in these samples. It is possible that impact strength may be a more important variable when the performance of carbonate rock types is considered.

Impact loss had a significant correlation (r= 0.63) with depth of milling, or, a greater depth of cut was taken with weaker aggregates.

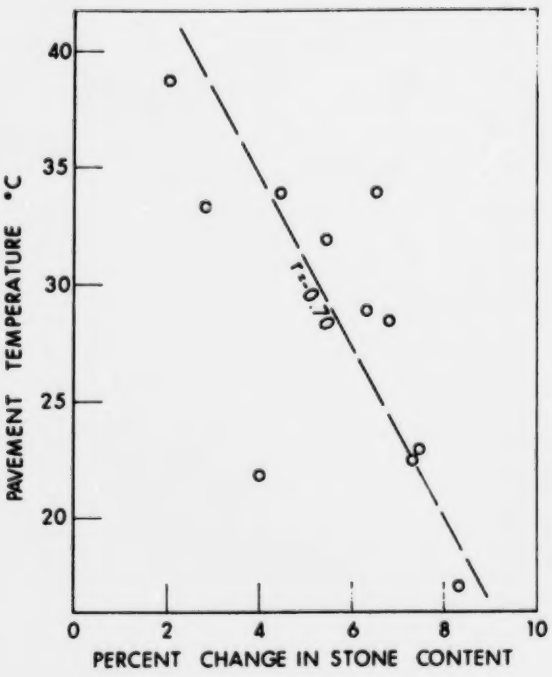

Figure 2. Pavement temperature and change in stone content of milled asphalt pavement.

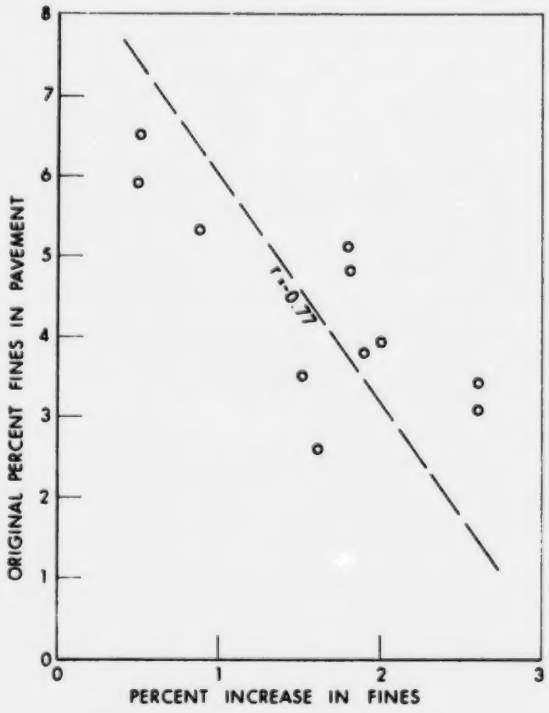

Figure 3. Original fines in asphalt pavement and increase in fines due to milling of the pavement.

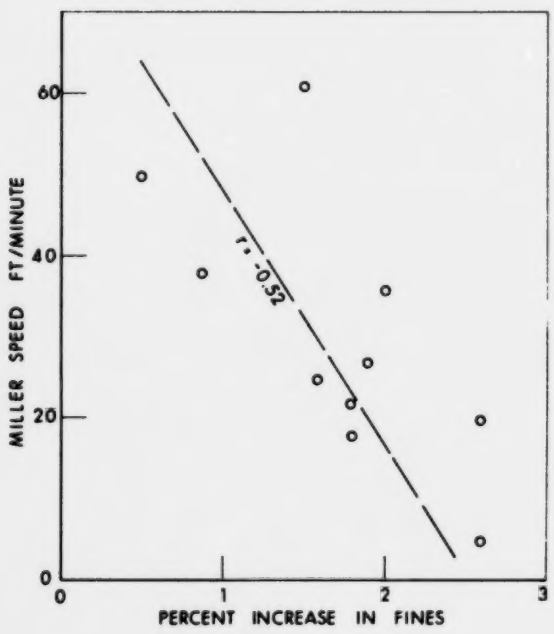

Figure 4. Miller speed and increase in fines due to milling of asphalt pavement.

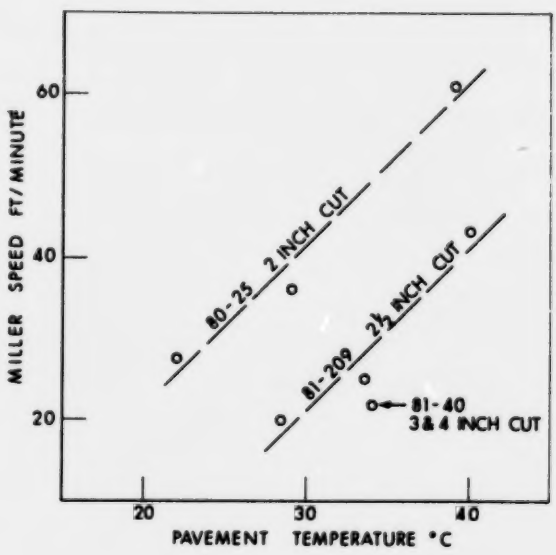

Figure 5. Miller speed and pavement temperature and depth of cut by milling equipment.

RESULTS AND DISCUSSION cont'd

Multiple Regression Analysis

No single variable was found that had a highly significant correlation with the various measures of aggregate degradation. As a result, following the simple regression analysis, multiple regression analysis was done. The purpose of this was primarily to get a better understanding of the variables most closely related to the different measurements of aggregate breakdown. The equations that were developed have extremely limited application for predicting aggregate degradation, because two of the most important variables, temperature and speed, are not known before milling takes place. The results are presented in Table 4.

EQUATION	Correlation Coefficient
FM Change = 0.01(T) + 0.003(S) -0.07(F) -0.52	r= 0.78
Stone Change = 0.24(T) + 0.08(S) -0.7(F) -12.5	r= 0.82
Fines Change = -0.02(MS) -0.004(S) -0.41(F) + 4.1	r= 0.87

Where T= pavement temperature in ^{o}C,
S= original pavement stone content in percent,
F= original pavement fines content in percent,
MS= miller speed in ft/min.
FM= fineness modulus

TABLE 4 - Multiple regression analysis of the eleven samples (Appendix 1, Table 8) gave these equations for predicting aggregate degradation due to cold milling.

In each equation the main variables contributing to the prediction are pavement temperature or miller speed and original fines content of the pavement. The original stone content makes a much smaller contribution to the multiple regression coefficient. Stone content was included however because it is a known quantity and it did improve the correlation a small amount in each case.

RESULTS AND DISCUSSION cont'd

It can be seen that the change in F.M. and stone content depends on the temperature, original stone content and original fines content of the pavement. Increase in fines content depends on miller speed, original stone content and original fines content of the pavement. These equations only apply to the set of data from which they were derived. To use these equations for prediction, the following criteria must be met:

1. CMI or Barber-Greene equipment must be used.
2. The asphaltic concrete must contain igneous and metamorphic rock types.

The influence of miller speed on generation of fines is interesting. In Table 3 and Figure 4 it can be seen that there is a limited inverse correlation between increase in fines and miller speed (r=-0.52).As miller speed increases, the generation of fines is reduced. Bellner (1978) and Walton and Levien (1978) noted that as the speed of CMI milling equipment increased, the gradation of the milled pavement became coarser. They restricted speed to 30-35 feet per minute and 25 feet per minute respectively to obtain their desired gradations. The coarser the fragments of asphalt pavement, the less work is done on each unit of milled material and hence less fines are generated. Thus the inverse correlation of increase in fines with miller speed is not so unreasonable.

GENERAL OBSERVATIONS

In the course of conducting this investigation a number of general observations were made about problems, and solutions to problems, that arise in cold milling operations. While these observations did not constitute a formal part of the investigation their inclusion is worthwhile.

Safety

Safe work practices are a necessity when working near milling machines. The machines are noisy, requiring the use of hearing protection. Traffic control procedures were sometimes inadequate. An O.P.P. officer warned one contractor that his flag persons were in violation of the Highway Traffic Act (Flagging Procedures). Tragically, on contract 80-25 a member of the milling crew was killed when he stepped backward into the ongoing stream of traffic.

Experience of Operators

The use of these complex, expensive machines is relatively new. Those crews who had the most experience had the smoothest operation, fewest equipment breakdowns and gave the best final product. The provision of an organized, dedicated, experienced crew and sufficient trucks for hauling is essential for a satisfactory, cost effective operation.

Contamination of Reclaimed Material

Usually, partial depth milling presents little opportunity for contamination by other materials. Sometimes re-milling of pavements is necessary to establish correct crossfall and grade. The product of this re-milling is usually finer in gradation. This material should be stockpiled separately otherwise the increase and variability in fines may lead to mix control problems.

In full depth milling, the underlying granular material adheres to the reclaimed pavement. Northwestern Region estimates this contamination may constitute up to 10 percent of the total reclaimed material. When pavement thickness fluctuates close to milling depth the miller may break through and extract considerable quantities of the underlying material.

GENERAL OBSERVATIONS cont'd

Pre Contract Engineering Investigation

On one contract the pavement thickness was stated to be 3 inches. The contractor milled off the top 2 inches of pavement. Sometimes the pavement was not 3 inches thick, the miller broke through the pavement into the underlying material leading to contamination problems.

On another contract, the operators were expecting to change milling teeth about once a day at a cost of about $3000. Because the pavement contained significant amounts of hard, abrasive aggregate they had to change teeth twice a day.

Petrographic examination has been conducted by MTC in an effort to provide the contractor with information about the types of rock in the pavement. A Petrographic Number has not been reported as it is not appropriate for purposes of determining aggregate hardness. The major rock types are identified and their weight percentage determined. The tentative test method used by the Thunder Bay regional laboratory is presented in Appendix 4.

A number of contractors have developed their own test procedures to determine pavement hardness. One contractor has tried using a portable saw with a tungsten carbide cutting wheel to make a cut of predetermined length and depth. Pavement temperature is also recorded at the time of cutting. This data is then correlated with the actual experience of milling teeth wear and cost of milling the pavement.

In summary, the provision of reliable information about the existing condition and composition of the pavement is necessary for judging and preventing problems in cold milling and in the subsequent recycling of the reclaimed material.

CONCLUSIONS

1. Cold milling causes degradation of aggregate in reclaimed pavement. On the contracts studied in this investigation, the fines increased about 2 percent with a range of 0.9 to 3.2 percent. Stone content was reduced about 6 percent with a range of 3.8 to 8.1 percent.

2. On the pavements studied, the following variables influenced aggregate degradation.
   a) Machine type
   b) Pavement temperature
   c) Milling machine speed

3. It is not possible to reliably predict the extracted aggregate gradation of reclaimed, cold milled pavement. This is due to the significant influence of pavement temperature and milling machine speed on aggregate degradation. These variables are not known prior to milling. Stone degradation is related to pavement temperature and original stone and fines content of the pavement. Generation of fines is related to milling machine speed and original fine and coarse aggregate content of the pavement.

4. The rock type and strength of the coarse aggregate did not have as important an influence on degradation as had been expected. Rock type however, has a significant effect on the wear of the miller teeth, thus affecting the economics of the operation. It should be noted that most of this investigation was done on igneous and metamorphic rocks rather than the softer, sedimentary types.

5. Greater quantities of reliable data are needed about aggregate degradation in cold milling. A great deal of cold milling is being done yet there is no published report that describes studies of aggregate degradation in this process. High recycling ratios of milled material will only be achieved when the generation of fines and degradation of stone is understood, predicted, and controlled.

RECOMMENDATION

The conclusions reached in this study are based on limited data. As a result, these only apply to specific types of aggregates, equipment and limited ranges of pavement temperature and milling machine speed. If further knowledge about degradation is desired, more detailed study is necessary. In which case:

> *It is recommended that the study be continued to develop more information about aggregate degradation during cold milling. Two contracts should be studied in detail. One should be a carbonate aggregate pavement, the other an igneous aggregate pavement.*

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APPENDIX I

SUMMARY OF LABORATORY TEST AND CONTRACT DATA

SAMPLE DATA		TEST DATA										
		Asphalt Percent	Cumulative Percent Retained, Extracted Aggregate 9.5 mm	6.7 mm	4.75 mm	2.36 mm	1.18 mm	600 µm	300 µm	150 µm	75 µm	Pass 75 µm
PAVEMENT SAMPLE	Slab 1	*	7	17	27.5	42	53	67	81	91	95.6	4.4
	Slab 2	*	8	20	31.1	44	55	69	83	92	95.7	4.3
	Slab 3	*	6	19	30.4	43	54	67	81	91	95.6	4.4
	Mean		7.0	18.7	29.7	43.0	54.0	67.7	81.7	91.3	95.6	4.37
MILLED SAMPLE	A	5.07	7	15	24.4	39	51	65	80	90	94.8	5.2
	B	5.01	7	16	24.6	41	52	67	81	90	94.5	5.5
	Mean	5.04	7.0	15.5	24.5	40.0	51.5	66.0	80.5	90.0	94.6	5.35

Table 5: Detailed test results for sample from Contract 79-23, Hwy. 41 north of Napanee. Note good agreement between individual measurements for pavement and milled samples.

* Test results unreliable.

CONTRACT Nº AND LOCATION	SAMPLE NUMBER	PAVEMENT TEMPERATURE IN °C	MILLED PRODUCT TEMPERATURE IN °C	CHANGE IN TEMPERATURE IN °C	MILLER SPEED (ft/min)	FINENESS MODULUS (F M) *	FINENESS MODULUS CHANGE	PERCENT RETAIN 4.75 mm *	RETAIN 4.75 mm CHANGE IN PERCENT	PERCENT PASS 75 µm *	PASS 75 µm CHANGE IN PERCENT	PERCENT MOISTURE
80-25 Kaladar	1	32.0	38.5	+6.5	18	5.68	-0.57	40.8	-5.4	4.8	+1.8	-
80-25 Kaladar	2	21.9	29.0	+7.1	27	5.61	-0.28	41.5	-4.0	3.8	+1.9	-
80-25 Kaladar	3	29.0	39.0	+10.0	36	5.49	-0.43	40.4	-6.3	3.9	+2.0	-
80-25 Kaladar	4	39.0	43.5	+4.3	61	5.64	-0.14	42.9	-2.0	3.5	+1.5	-
81-40 Huntsville	1	34.0	34.0	0.0	22	5.17	-0.45	33.9	-6.5	6.5	+0.5	-
81-40 Huntsville	2	34.0	38.0	+4.0	22	5.57	-0.44	39.4	-4.4	5.1	+1.8	-
80-230 Fort Frances	1	17.0	19.5	+2.5	50	6.65	-0.63	57.6	-8.3	5.9	+0.5	3.0
80-230 Fort Frances	2	23.0	26.0	+3.0	38	6.27	-0.45	50.9	-7.4	5.3	+0.9	1.4
80-230 Fort Frances	3	27.0	27.0	0.0	55	6.10	-0.09	48.6	-1.9	5.8	+0.9	1.6
80-230 Fort Frances	4	-	-	-	-	6.39	-0.46	50.2	-6.3	4.9	+1.2	-

* Data from pavement samples. Note that change in FM, stone content and fines content is the difference between pavement test results and milled material test results.

Table 6: Laboratory test data and pavement data for samples collected.

CONTRACT Nº AND LOCATION	SAMPLE NUMBER	PAVEMENT TEMPERATURE IN °C	MILLED PRODUCT TEMPERATURE IN °C	CHANGE IN TEMPERATURE IN °C	MILLER SPEED (ft/min)	FINENESS MODULUS (F.M.) *	FINENESS MODULUS CHANGE	PERCENT RETAIN 4.75 mm *	RETAIN 4.75 mm CHANGE IN PERCENT	PERCENT PASS 75 µm *	PASS 75 µm CHANGE IN PERCENT	PERCENT MOISTURE
81-209 Kirkland Lake	1	28.5	28.5	0.0	20	5.52	-0.43	38.7	-6.8	3.4	+2.6	2.7
81-209 Kirkland Lake	2	33.5	39.0	+5.5	25	5.53	-0.20	39.7	-2.8	2.6	+1.6	0.6
81-209 Kirkland Lake	3	40.0	41.0	+1.0	43	-	-	-	-	-	-	0.6
80-232 Dryden	1	22.5	27.5	+5.0	-	5.45	-0.43	39.4	-7.3	3.2	+2.6	2.7
80-28 Smiths Falls	1	-	-	-	-	5.14	-0.44	35.4	-6.6	5.3	+1.7	-
80-28 Smiths Falls	2	-	-	-	-	5.33	-0.56	39.6	-9.6	4.1	+2.5	-
80-204 * Rous Lake	1	-	-	-	-	5.38	-0.01	39.7	-0.9	4.4	+1.1	-
80-214 Shekak River	1	-	-	-	-	5.41	-0.33	34.2	-3.8	3.8	+3.2	-
79-23 Napanee	1	-	-	-	-	4.92	-0.22	29.7	-5.2	4.4	+1.0	-

* Data from pavement samples. Note that change in FM, stone content and fines content is the difference between pavement test results and milled material test results.

Table 6: continued.

CONTRACT NUMBER AND LOCATION	COARSE AGGREGATE ROCK TYPE	MEAN FINENESS MODULUS CHANGE	MEAN RETAIN 4.75 mm CHANGE	MEAN PASS 75 µm CHANGE	MODIFIED IMPACT TEST	
					MEAN VALUE	RANGE
81-40 Huntsville	Gneiss - 65% Granite - 25% Carbonates - 10%	-0.45	-5.4	1.2	32.8	30.6 - 34.9
80-230 Fort Frances	Gneiss - 50% Granite - 40% Volcanic - 10%	-0.41	-6.0	0.9	20.0	18.3 - 21.4
81-209 Kirkland Lake	Granite - 65% Volcanic - 30% Gneiss - 5%	-0.32	-4.8	2.1	17.2	15.9 - 19.7
80-25 Kaladar	Trap Rock - 60% Granite - 30% Gneiss - 10%	-0.36	-4.4	1.8	13.4	12.0 - 15.2
80-232 Dryden	Granite - 65% Gneiss - 35%	-0.43	-7.3	2.6	25.8	24.8 - 26.8
80-28 Smiths Falls	Sandy Dolostone - 100%	-0.50	-8.1	2.1	-	-
80-204 * Rous Lake	Granite - 95% Carbonates - 5%	-0.01	-0.9	1.1	-	-
80-214 Shekak River	Granite } 68% Gneiss } Carbonates - 32%	-0.33	-3.8	3.2	-	-
79-23 Napanee	Limestone - 100%	-0.22	-5.2	1.0	-	-

* Suspect Test Data

Table 7: Summary of data by contract.

SAMPLE	PAVEMENT TEMPERATURE °C	MILLER SPEED FT/MIN.	ORIGINAL STONE CONTENT, PERCENT (+4.75 mm)	ORIGINAL -75 µm CONTENT, PERCENT	IMPACT LOSS, PERCENT	DEPTH OF MILLING IN INCHES	FINENESS MODULUS CHANGE	STONE CONTENT CHANGE, PERCENT	-75 µm CONTENT CHANGE, PERCENT
80-25.1	32.0	18	40.8	4.8	12.9	2.0	-.57	-5.4	1.8
80-25.2	21.9	27	41.5	3.8	13.4	2.0	-.28	-4.0	1.9
80-25.3	29.0	36	40.4	3.9	12.0	2.0	-.43	-6.3	2.0
80-25.4	39.0	61	42.9	3.5	15.2	2.0	-.14	-2.0	1.5
81-40.1	34.0	22	33.9	6.5	30.6	4.0	-.45	-6.5	0.5
81-40.2	34.0	22	39.4	5.1	34.9	3.0	-.44	-4.4	1.8
81-230.1	17.0	50	57.6	5.9	18.3	1.5	-.63	-8.3	0.5
81-230.2	23.0	38	50.9	5.3	20.6	2.0	-.45	-7.4	0.9
81-209.1	28.5	20	38.7	3.4	16.1	2.5	-.43	-6.8	2.6
81-209.2	33.5	25	39.7	2.6	19.7	2.3	-.20	-2.8	1.6
80-232.1	22.5	05	39.4	3.2	26.8	6.0	-.43	-7.3	2.6
MEAN	28.5	32	42.8	4.5	20.0	2.7	-.38	-5.3	1.6
MEDIAN	28.8	26	40.6	4.0	18.4	2.1	-.43	-6.3	1.7

Table 8: Raw data used for regression analysis. This data was collected on contracts operating in 1981 on pavements containing igneous and metamorphic rock types.

APPENDIX II

GRADING CHARTS

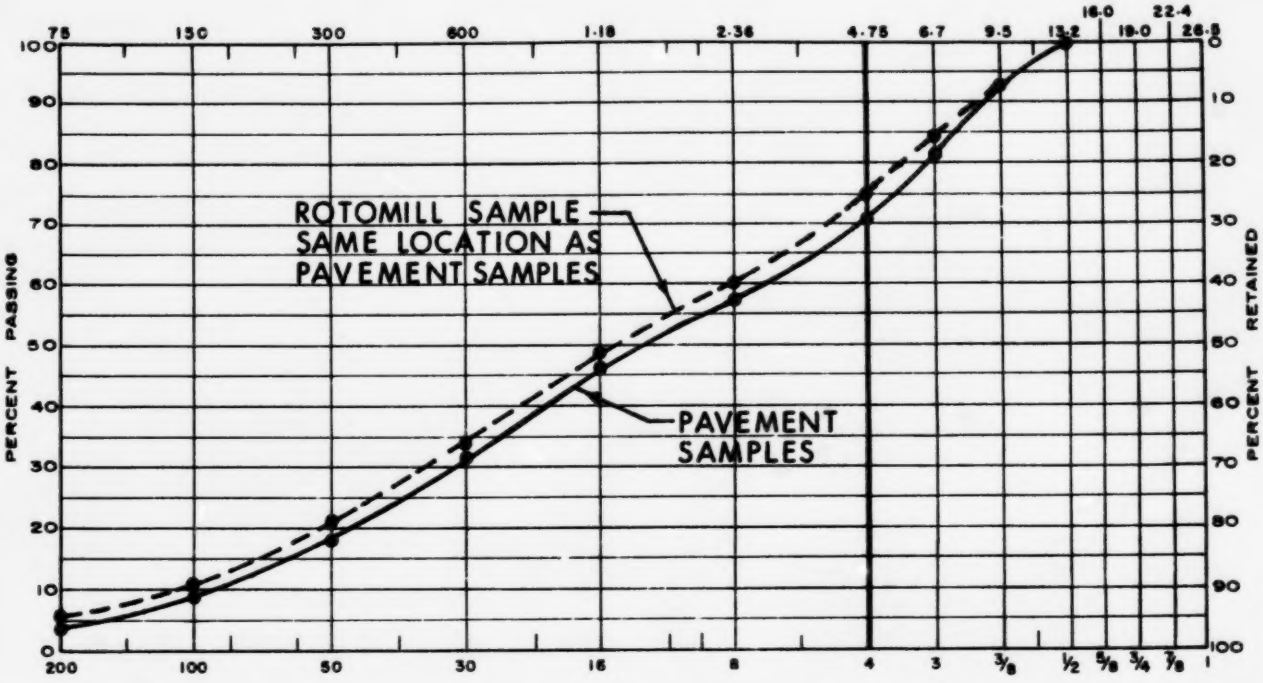


Figure 6: Change in grading during milling, Contract 79-23, Highway 41 north of Napanee.

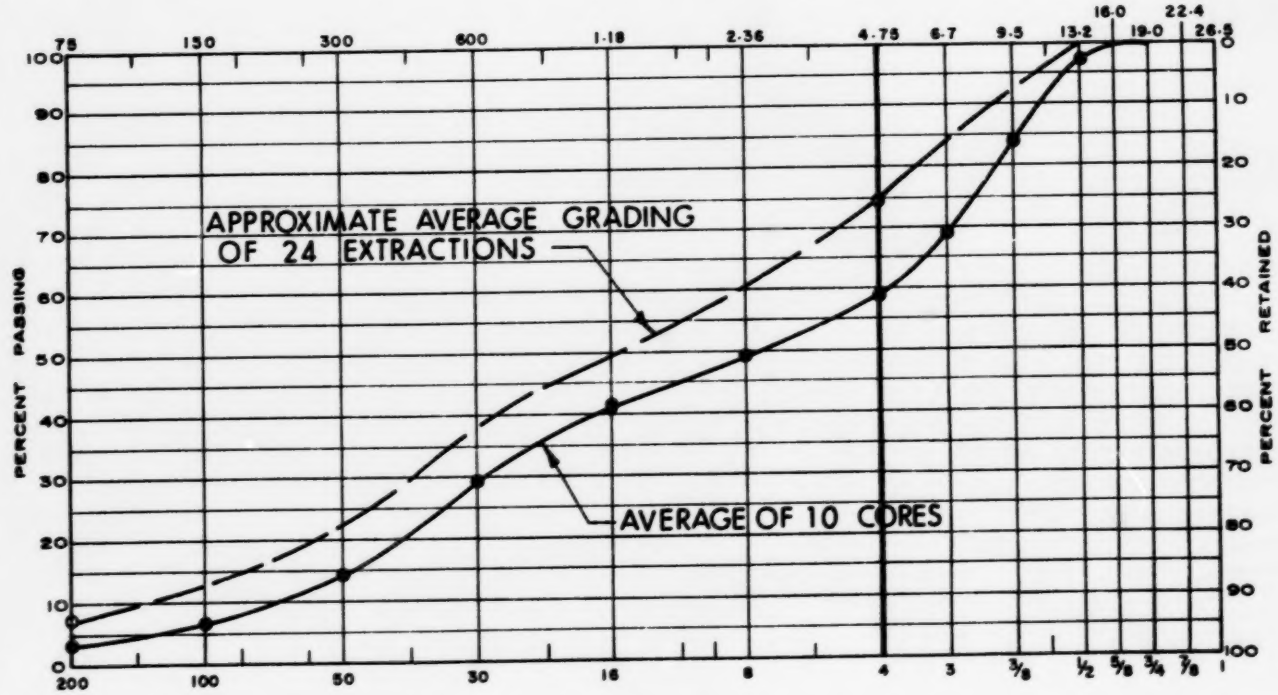


Figure 7: Change in grading between pre-contract engineering investigation (10 cores) and milling by SAKAI and CMI machines, Contract 80-28, Hwy. 15/29, north of Smiths Falls.

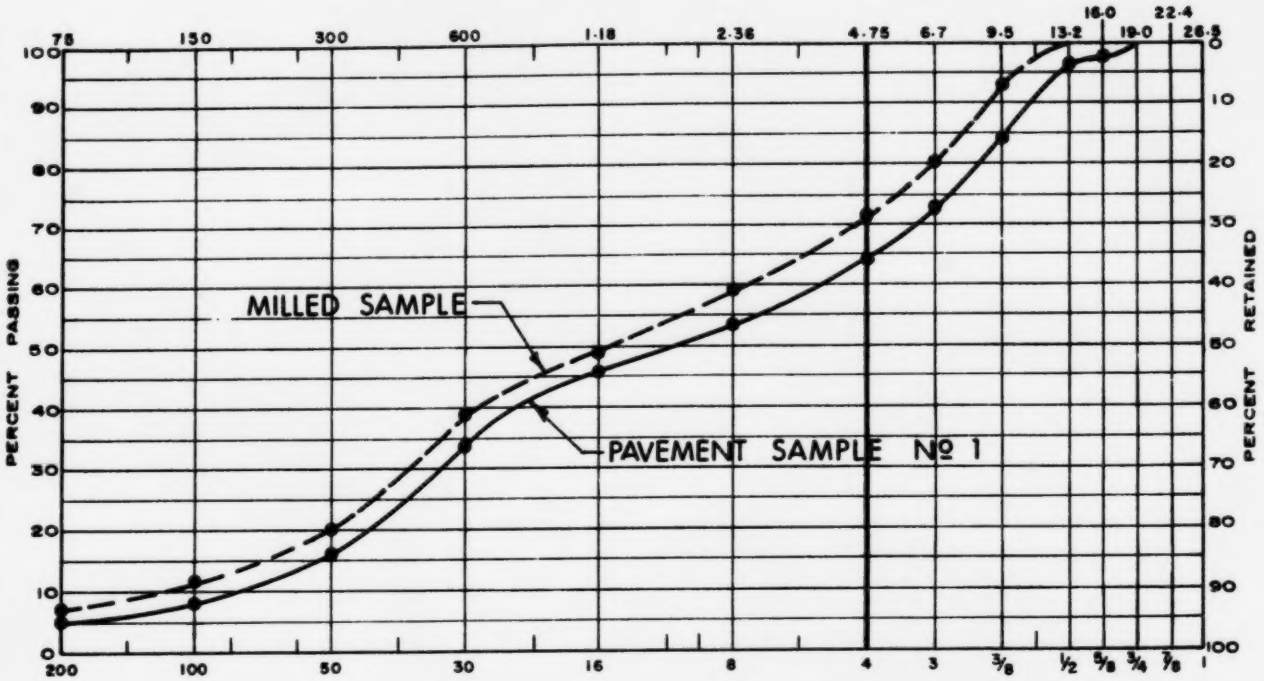


Figure 8: Change in grading caused by milling for CMI machine No. 1, Contract 80-28, Hwy. 15/29.

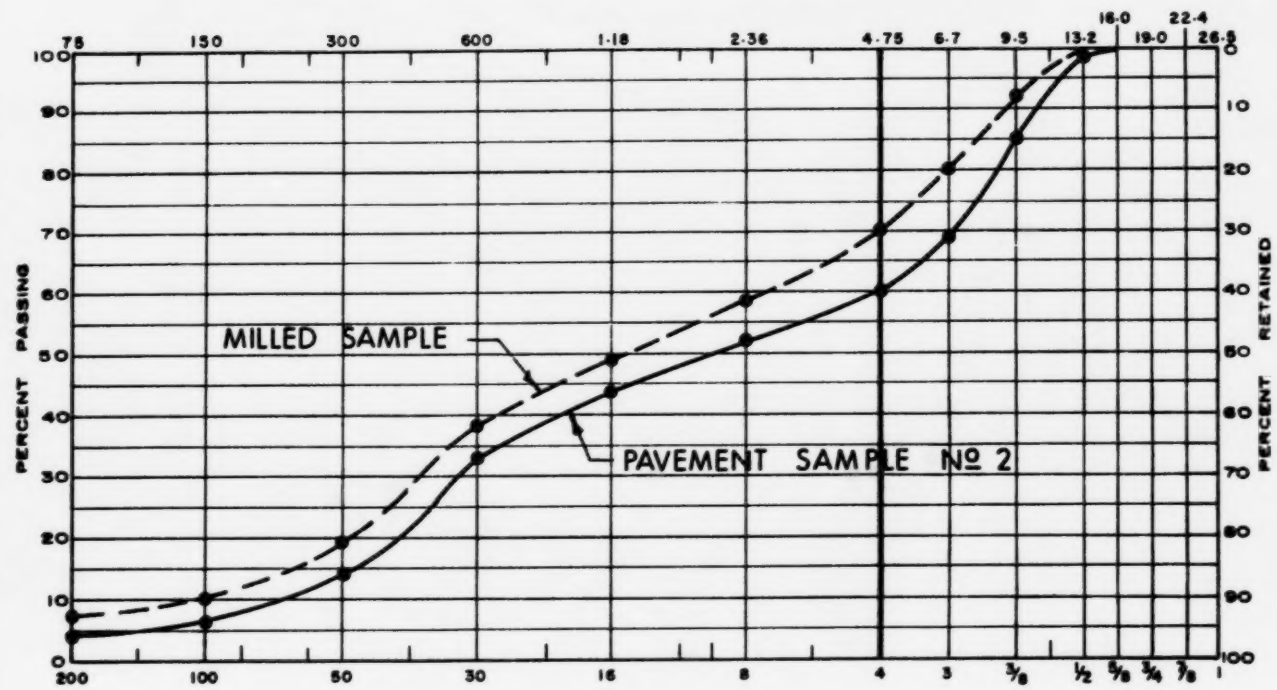


Figure 9: Change in grading caused by milling for CMI machine No. 2, Contract 80-28, Hwy. 15/29. This sample was taken from same lane and location as sample shown in Figure 4 above.

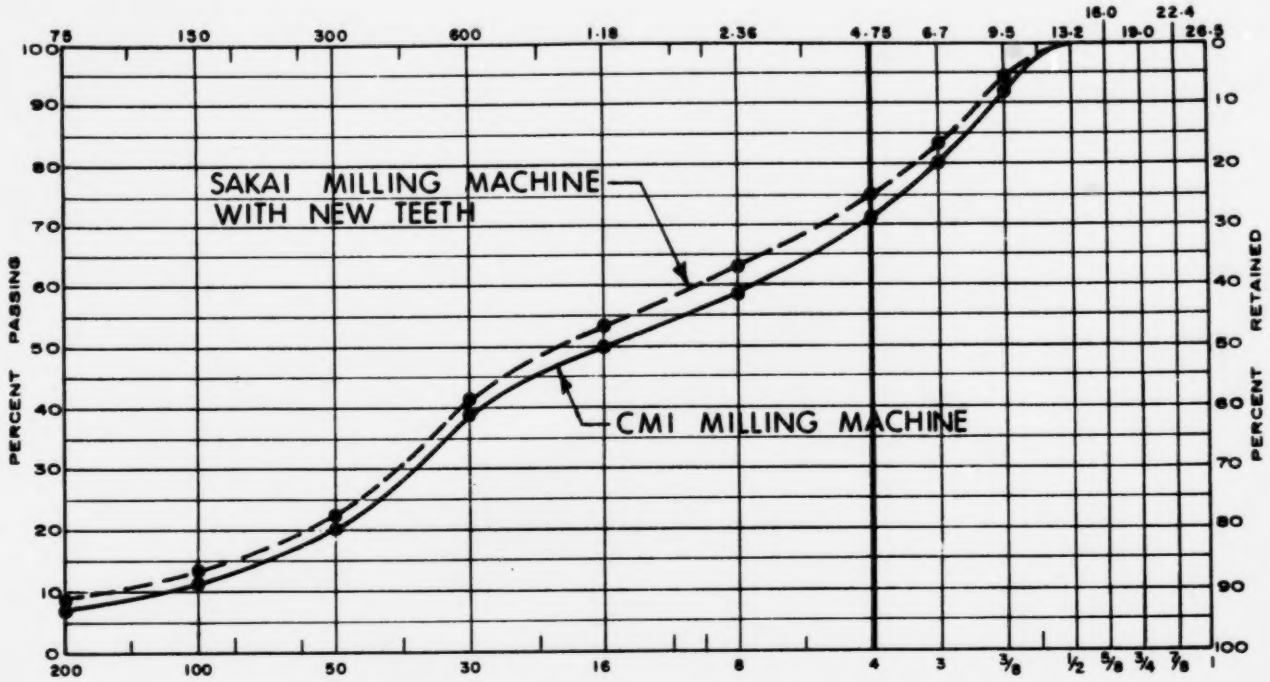


Figure 10: Comparison of aggregate gradings of asphalt milled by SAKAI and CMI machines from same lane and same location, Contract 80-28, Hwy. 15/29.

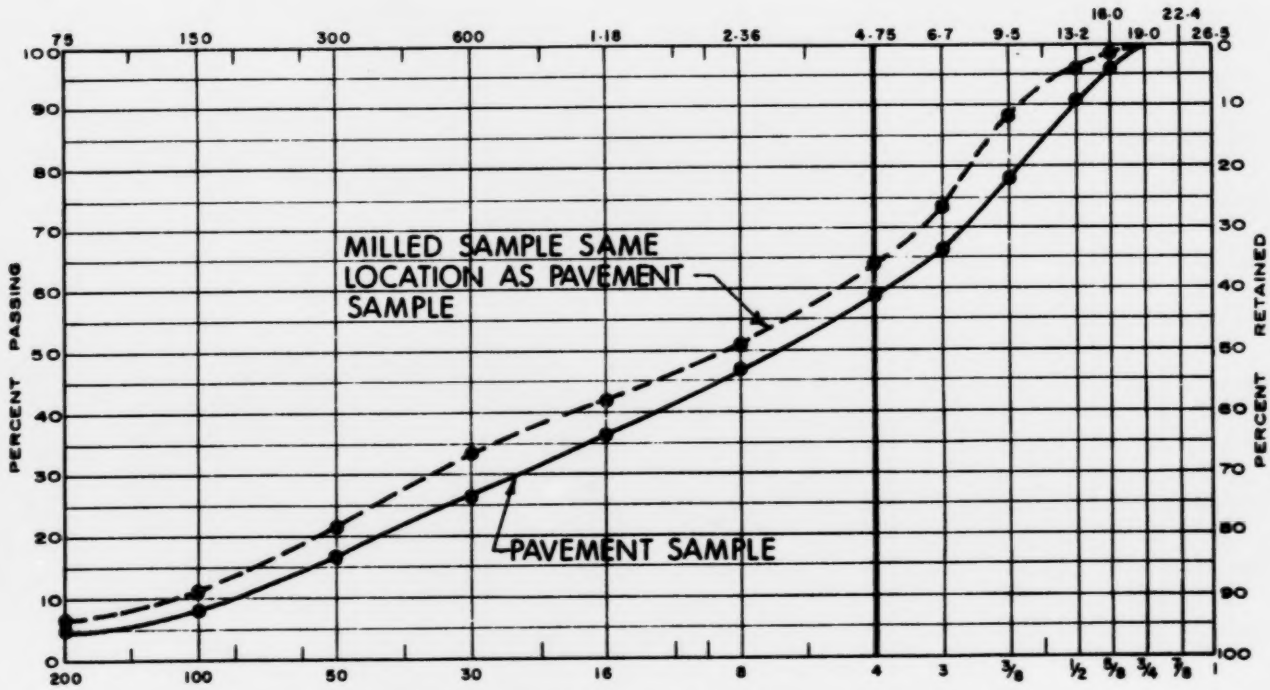


Figure 11: Change in grading caused by milling of binder course (H.L.8) on Contract 80-25, Hwy. 7 near Kaladar. (Sample No. 1).

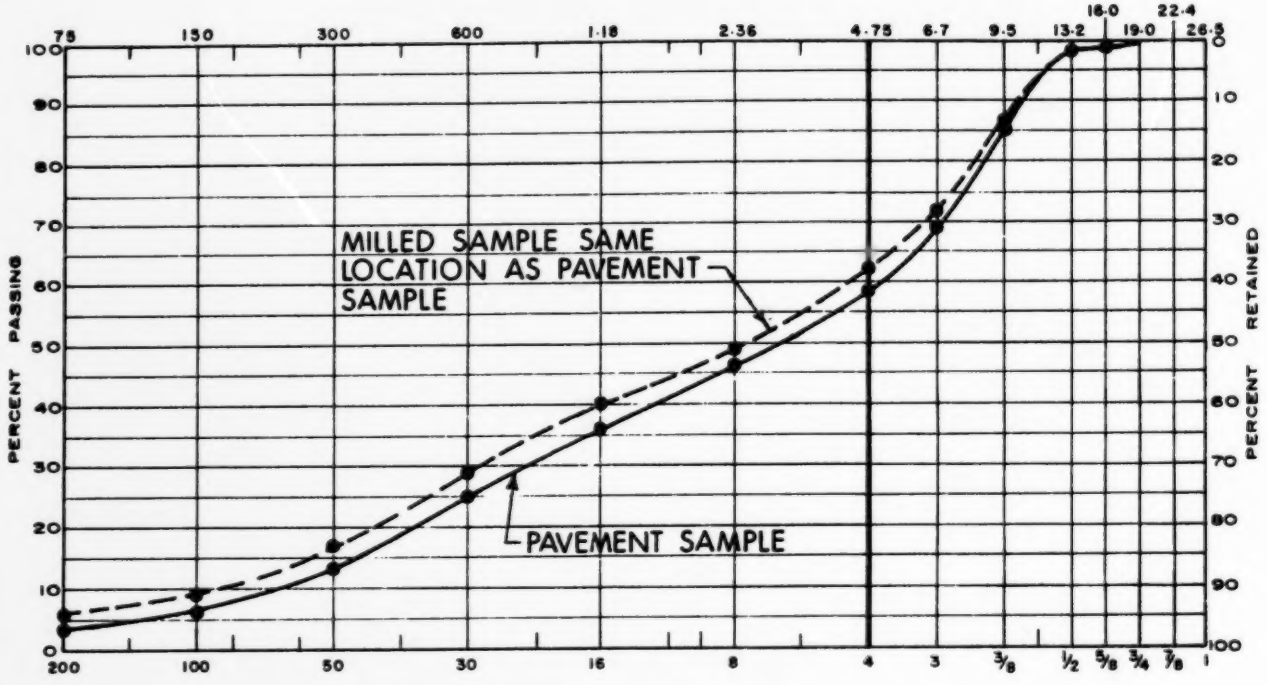


Figure 12: Change in grading caused by milling of surface course (Sample No. 2) on Contract 80-25, Hwy. 7.

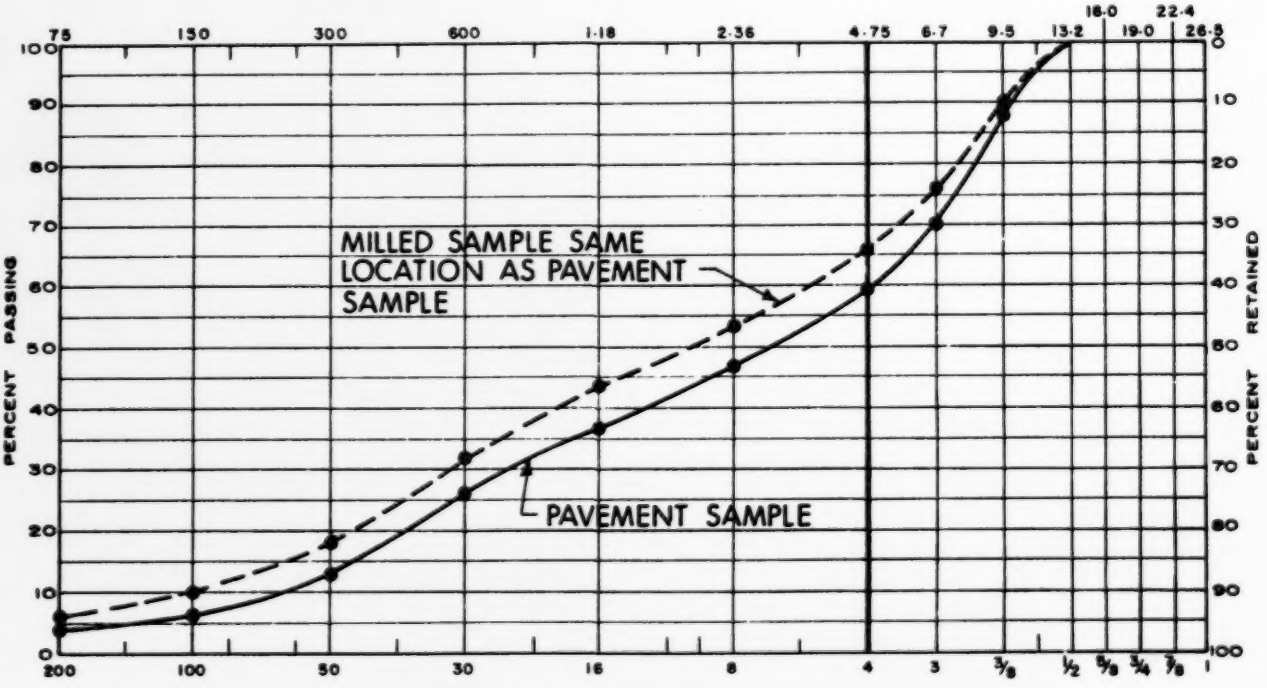


Figure 13: Change in grading caused by milling of surface course (Sample No. 3) on Contract 80-25, Hwy. 7.

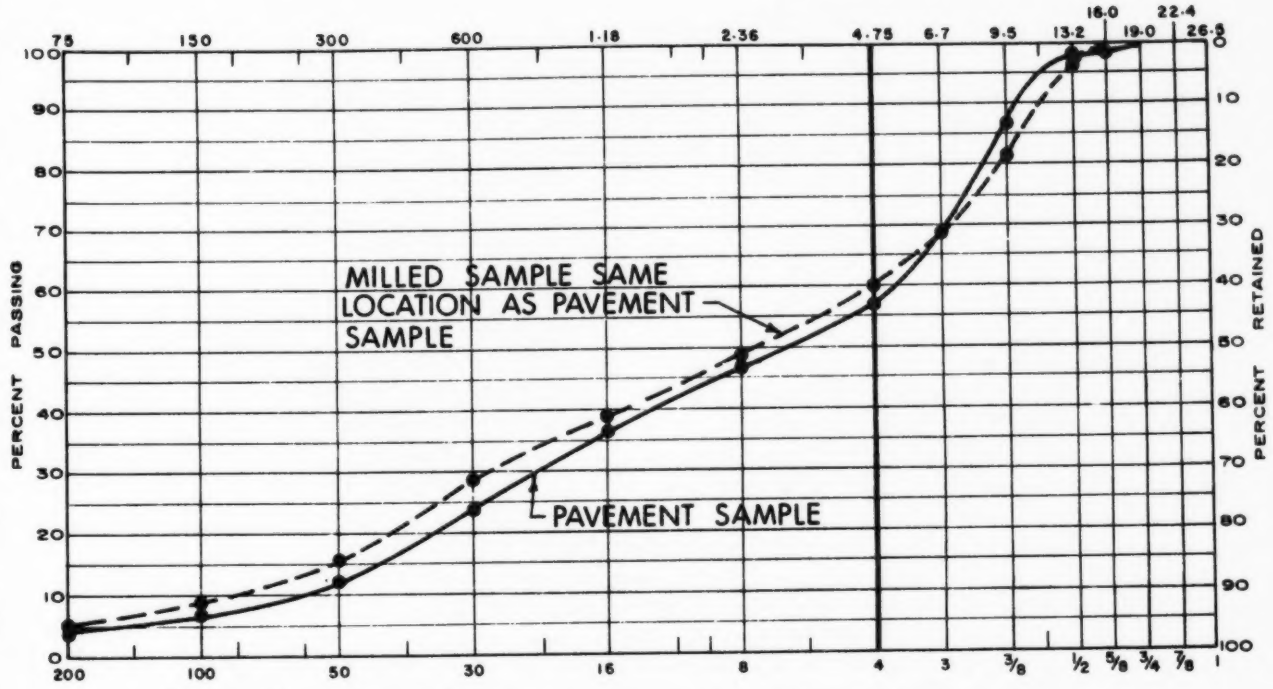


Figure 14: Change in grading caused by milling of surface course (Sample No. 4) on Contract 80-25, Hwy. 7.

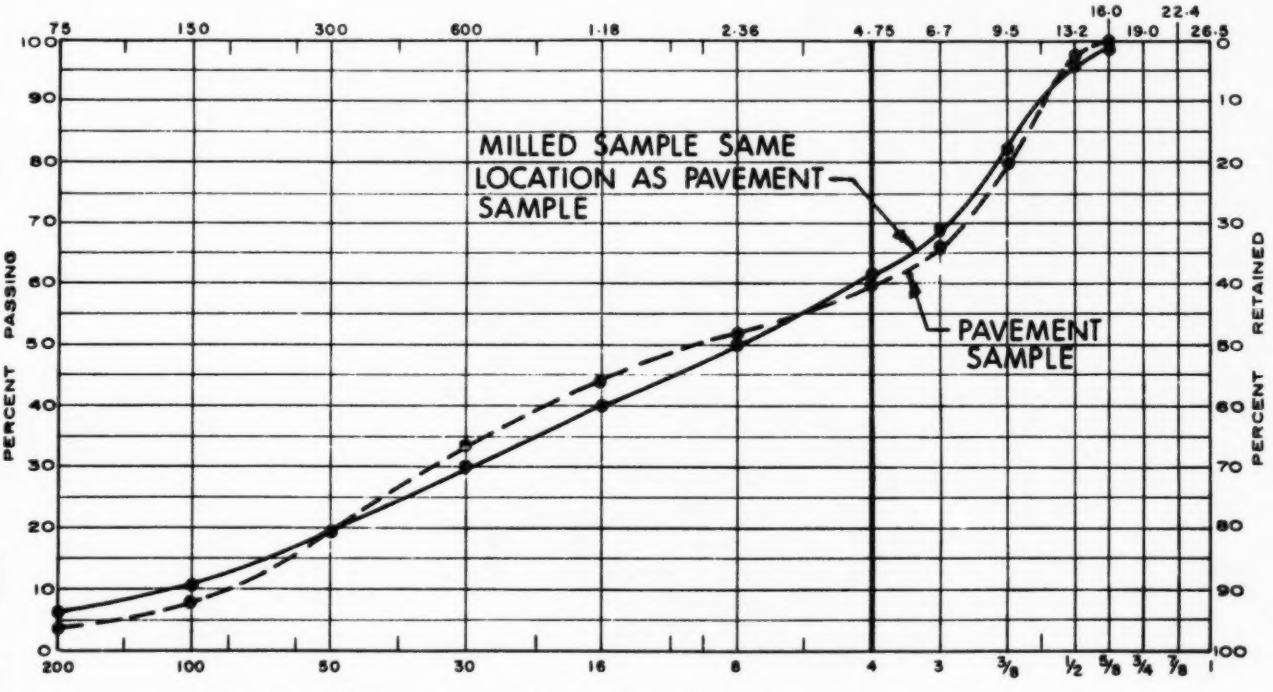


Figure 15: Change in grading caused by milling of surface course on Contract 80-204, Hwy. 17 east of Rous Lake. Validity of sample is doubtful.

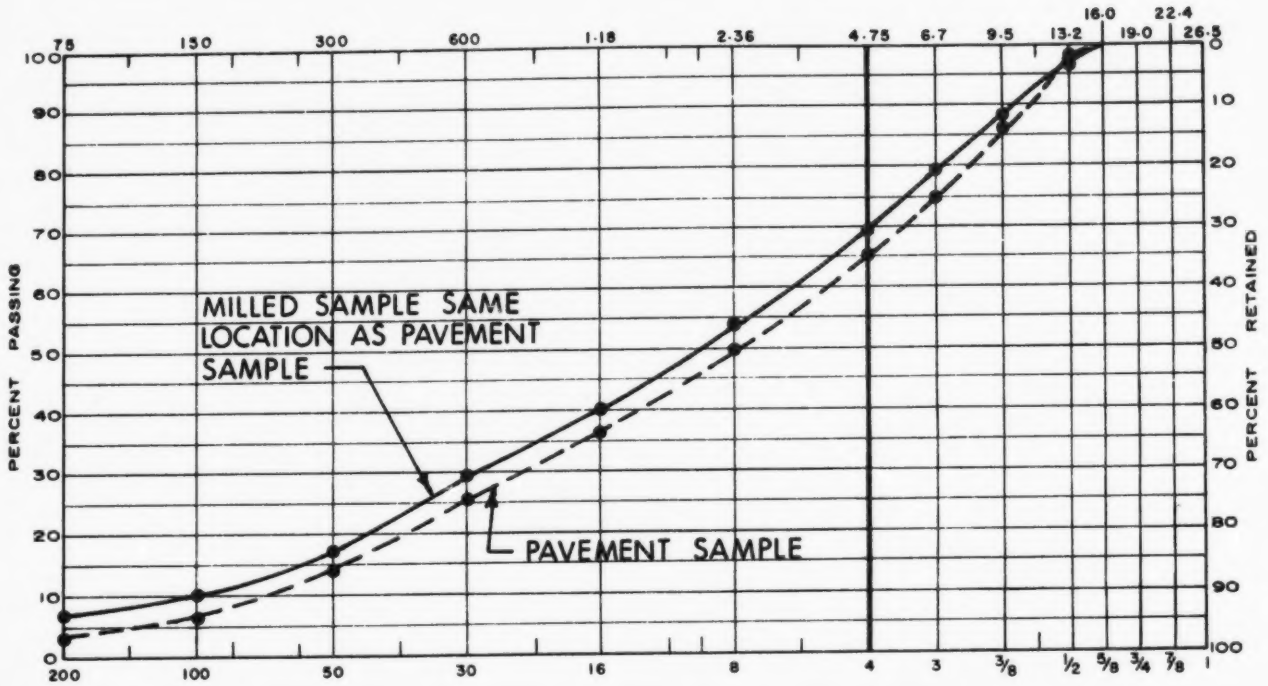


Figure 16: Change in grading caused by milling of surface course on Contract 80-214, Hwy. 11, west of Shekak river bridge.

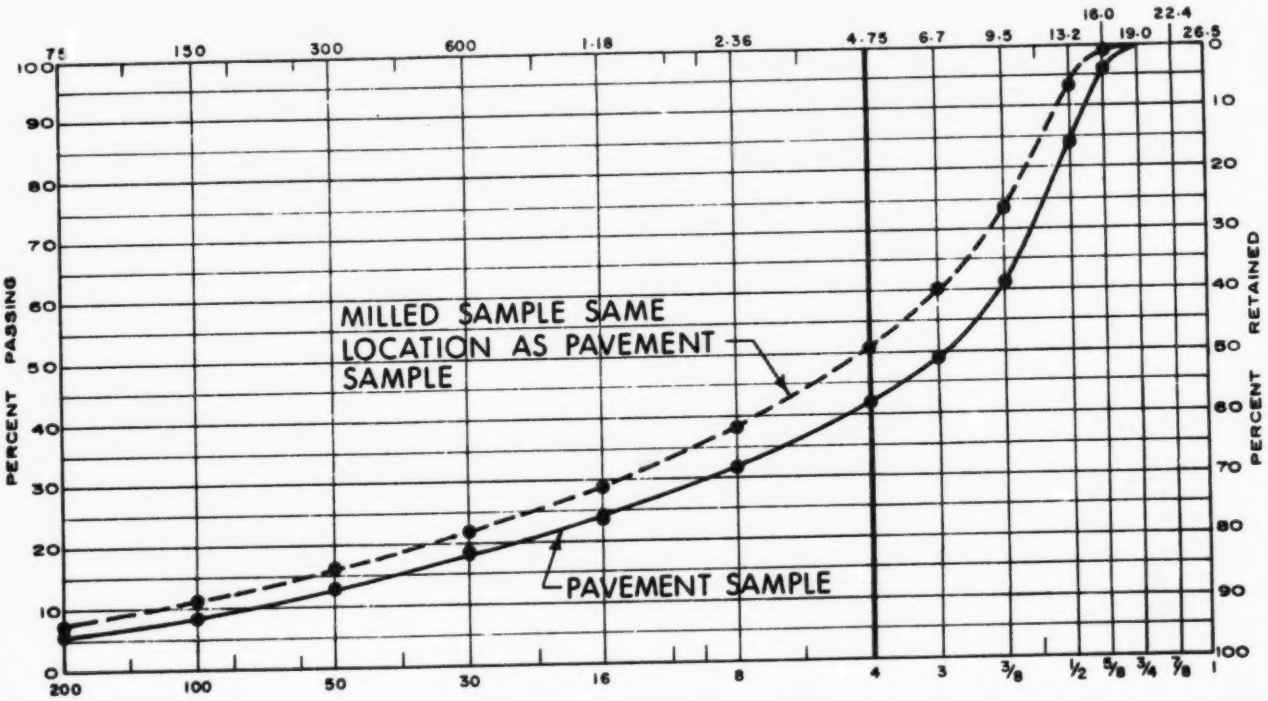


Figure 17: Change in grading caused by full depth milling on Contract 80-230, Hwy. 11 west of Fort Frances (Sample No. 1).

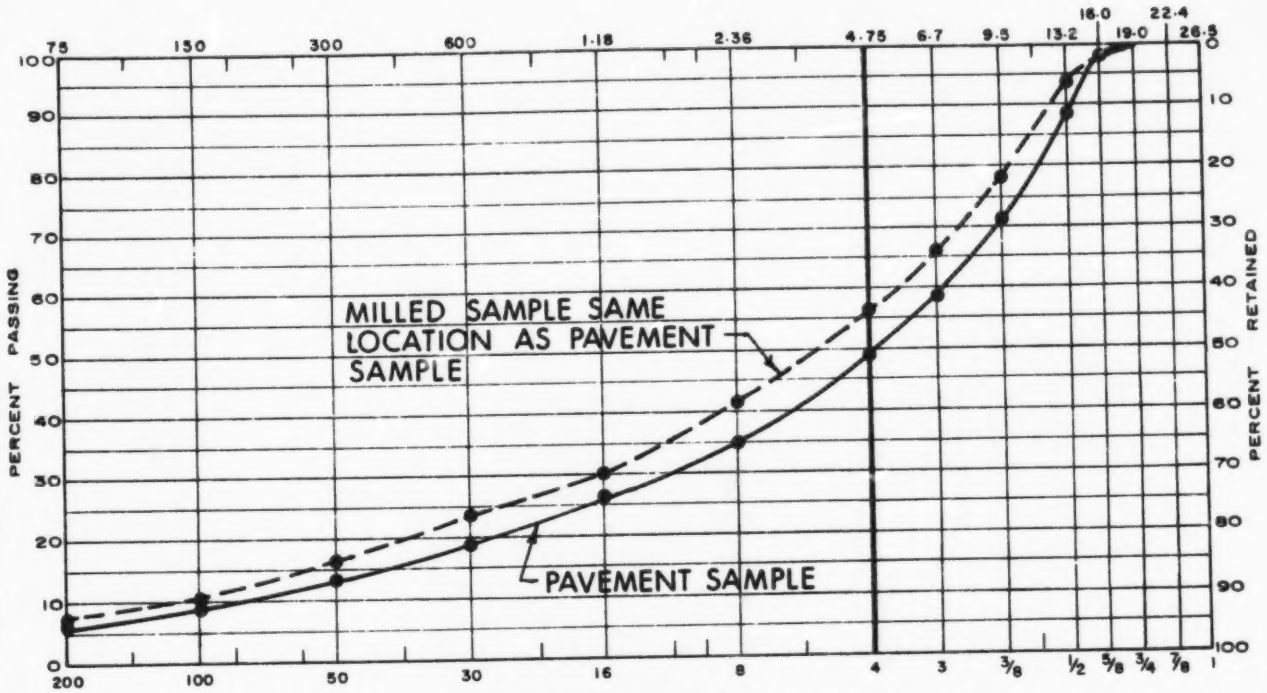


Figure 18: Change in grading caused by full depth milling on Contract 80-230, Hwy. 11 west of Fort Frances (Sample No. 2).

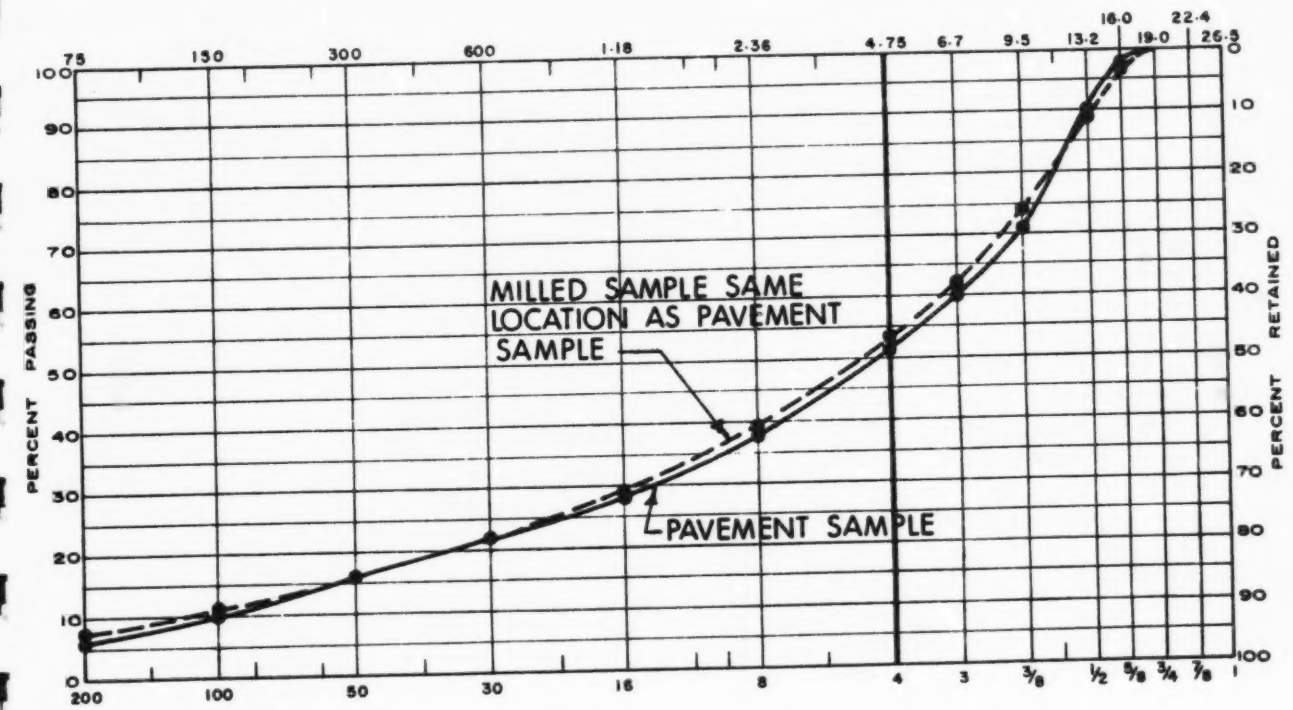


Figure 19: Change in grading caused by full depth milling on Contract 80-230, Hwy. 11 west of Fort Frances (Sample No. 3). Recent rainfall probably accounts for low amount of aggregate breakdown.

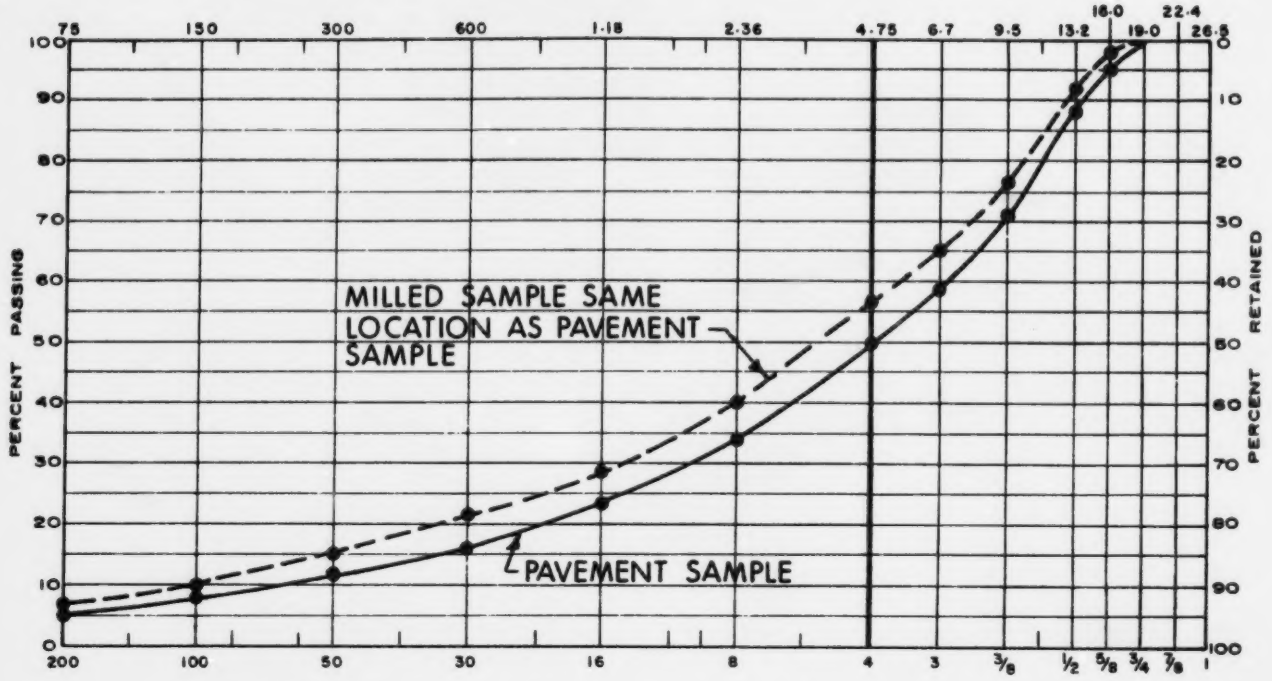


Figure 20: Change in grading caused by partial depth milling on Contract 80-230, Hwy. 11 west of Fort Frances (Sample No. 4).

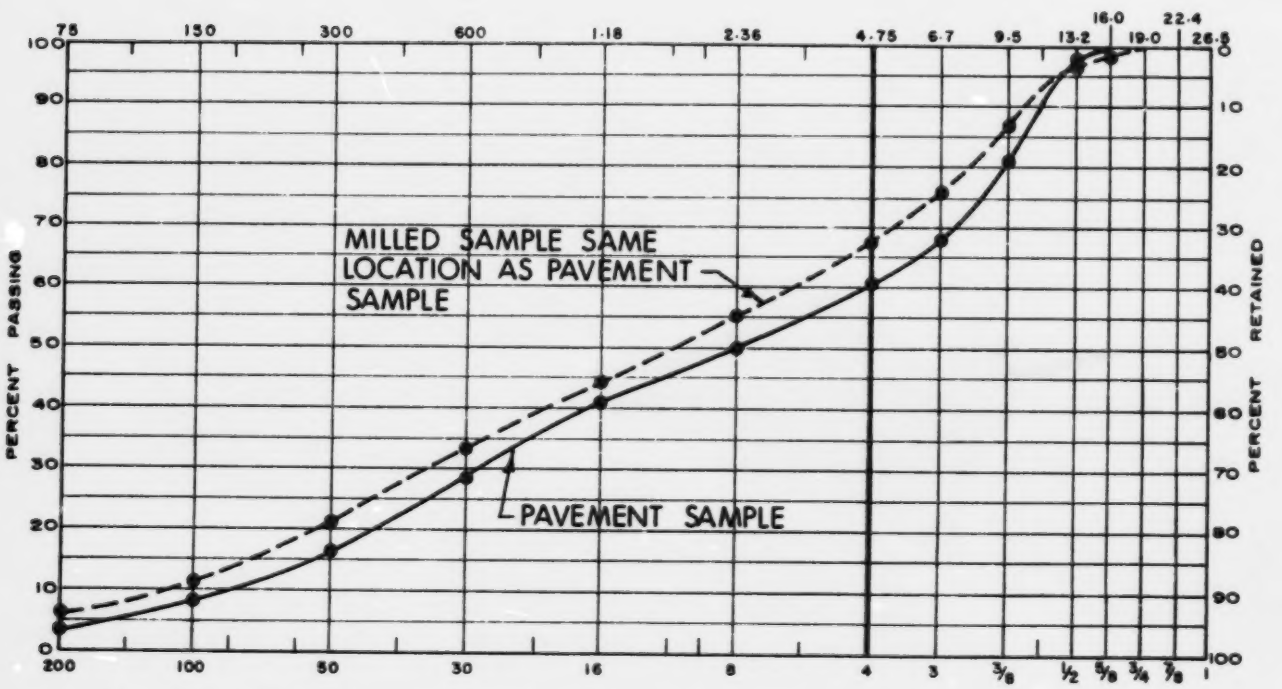


Figure 21: Change in grading caused by milling on Contract 80-232, Hwy. 17 near Dryden.

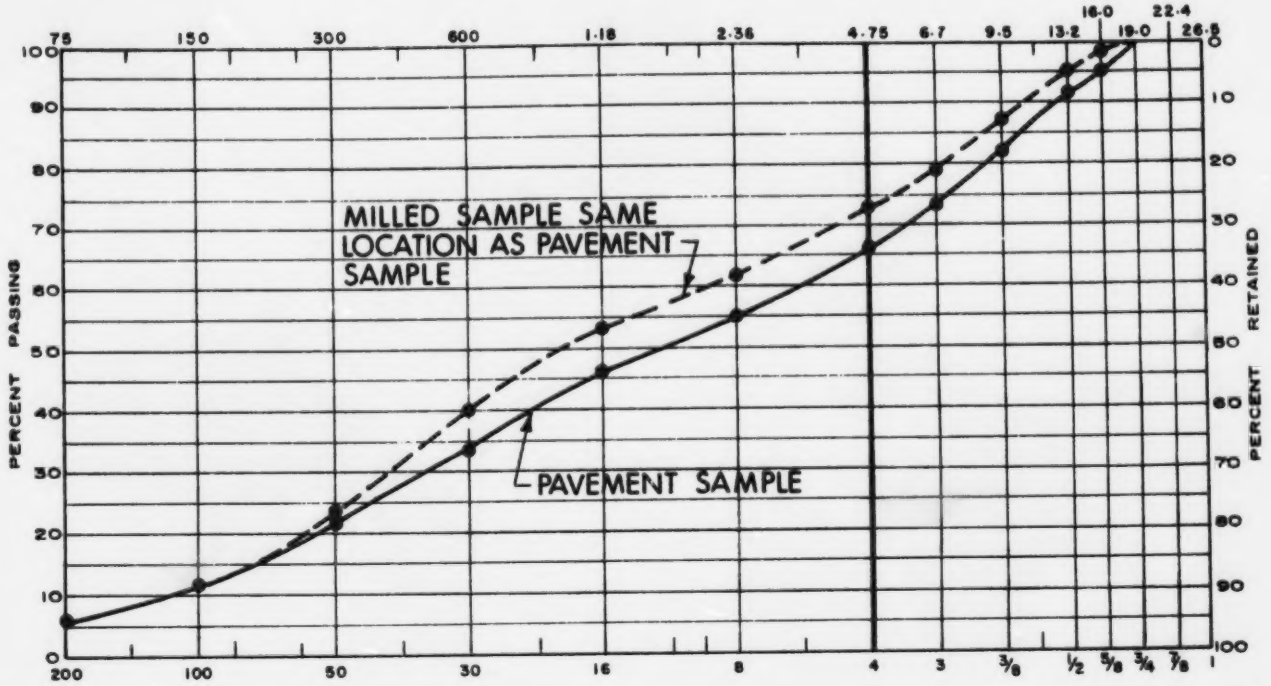


Figure 22: Change in grading caused by milling cold laid asphalt on Contract 81-40, Hwy. 141 near Huntsville (Sample No. 1).

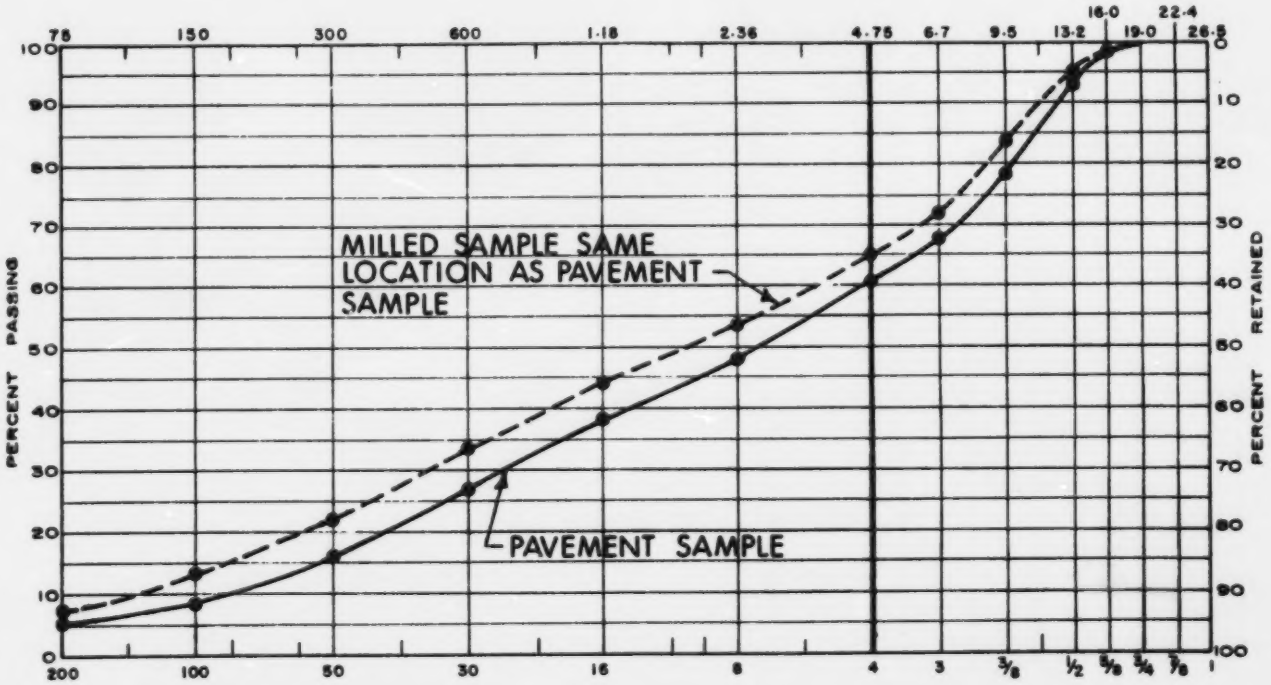


Figure 23: Change in grading caused by milling cold laid asphalt on Contract 81-40, Hwy. 141 near Huntsville (Sample No. 2).

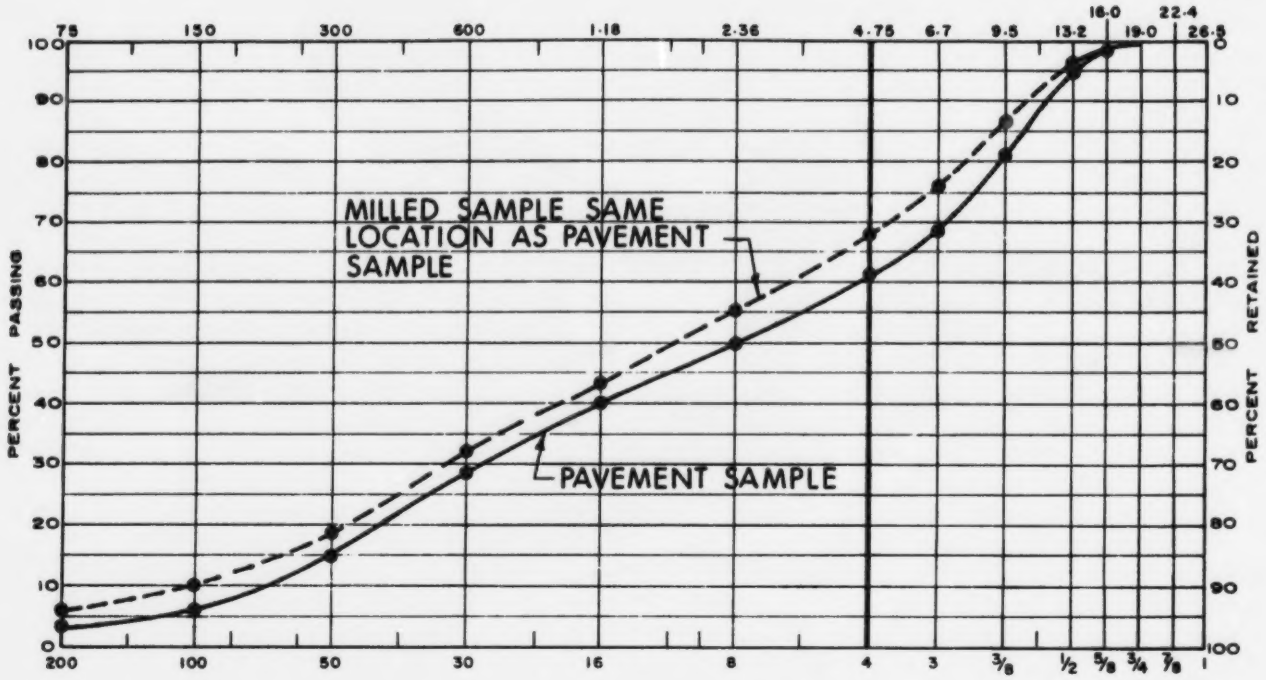


Figure 24: Change in grading caused by milling of surface course on Contract 81-209, Hwy. 11 south of Kirkland Lake (Sample No. 1).

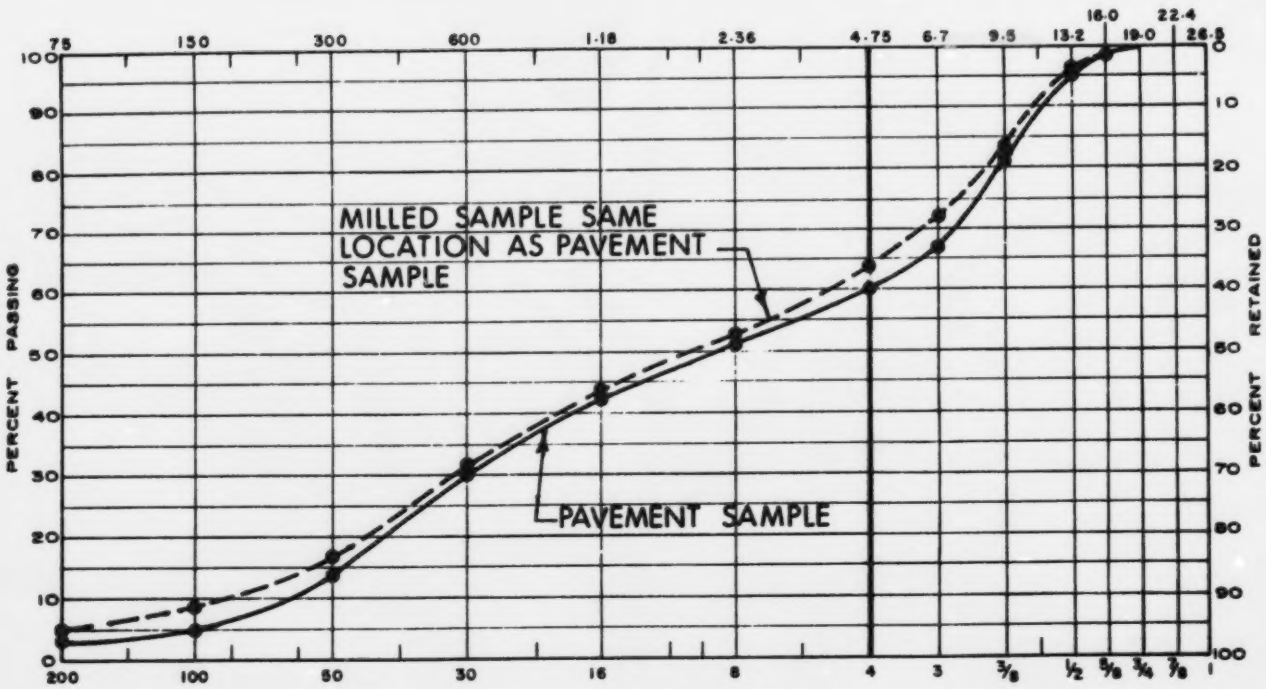


Figure 25: Change in grading caused by milling of surface course on Contract 81-209, Hwy. 11 south of Kirkland Lake (Sample No. 2).

APPENDIX III

PHOTOGRAPHS OF MILLING EQUIPMENT AND OPERATIONS

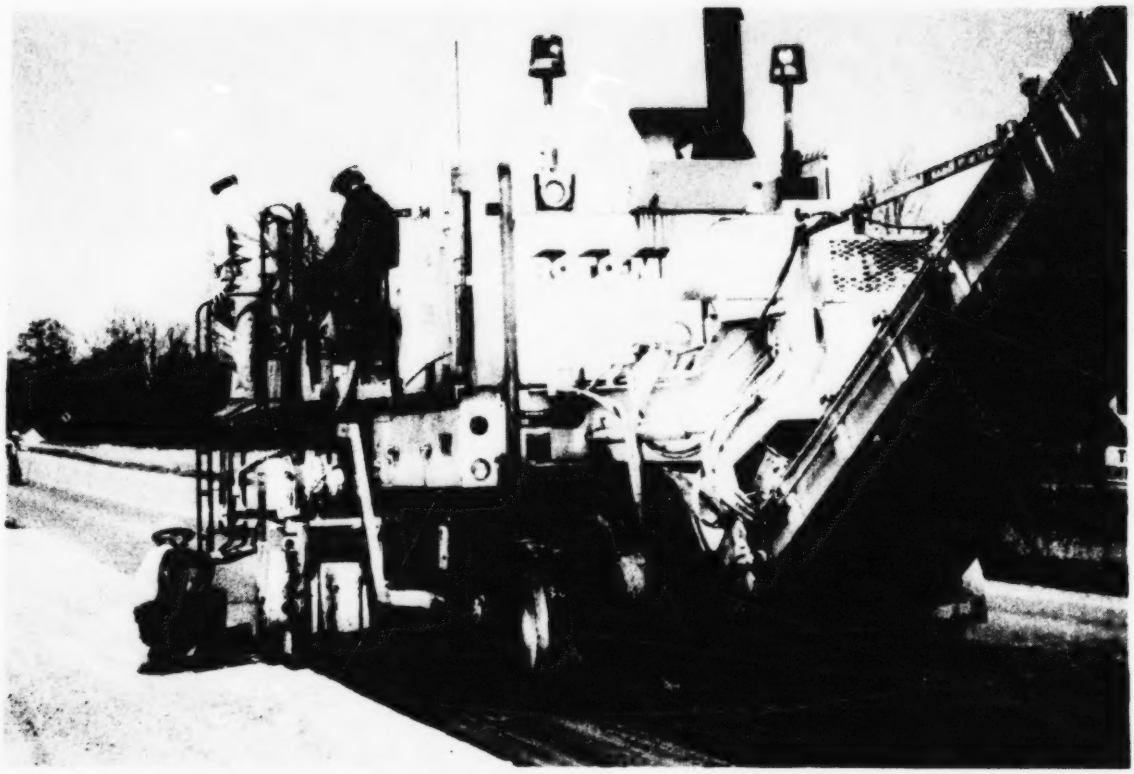


Figure 26: CMI (PR-750) 3.8 m milling machine on Contract 79-23, Hwy. 41 north of Napanee.

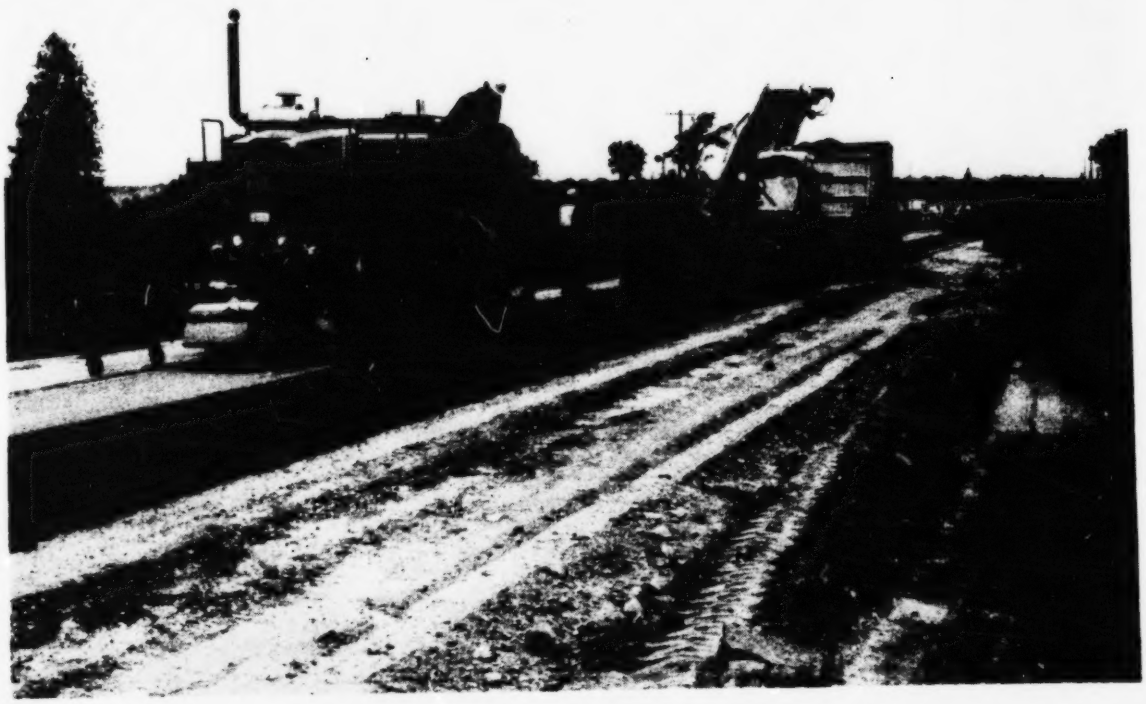
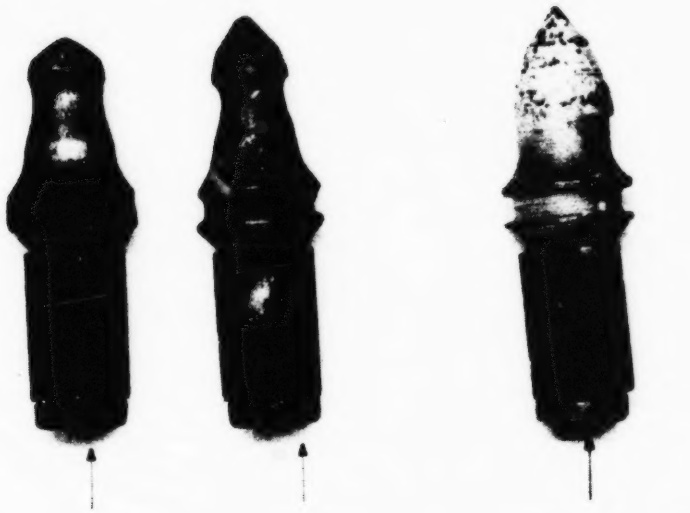


Figure 27: CMI (PR-225) 1.4 m milling machine on Contract 80-28, Hwy. 15/29 north of Smiths Falls. Note milled asphalt loading operation to right of milling machine.

Figure 28: Barber-Greene 3.7 m milling machine (RX-75) on Contract 80-232, Hwy. 17 near Dryden.

Figure 29: Close up of raised milling head and teeth on Barber-Greene (RX-75) milling machine.



BITS FROM C.M.I. AND BARBER - GREENE
MILLING MACHINES

Figure 30: Note hard, tungsten carbide tip on teeth wears less quickly than soft steel.

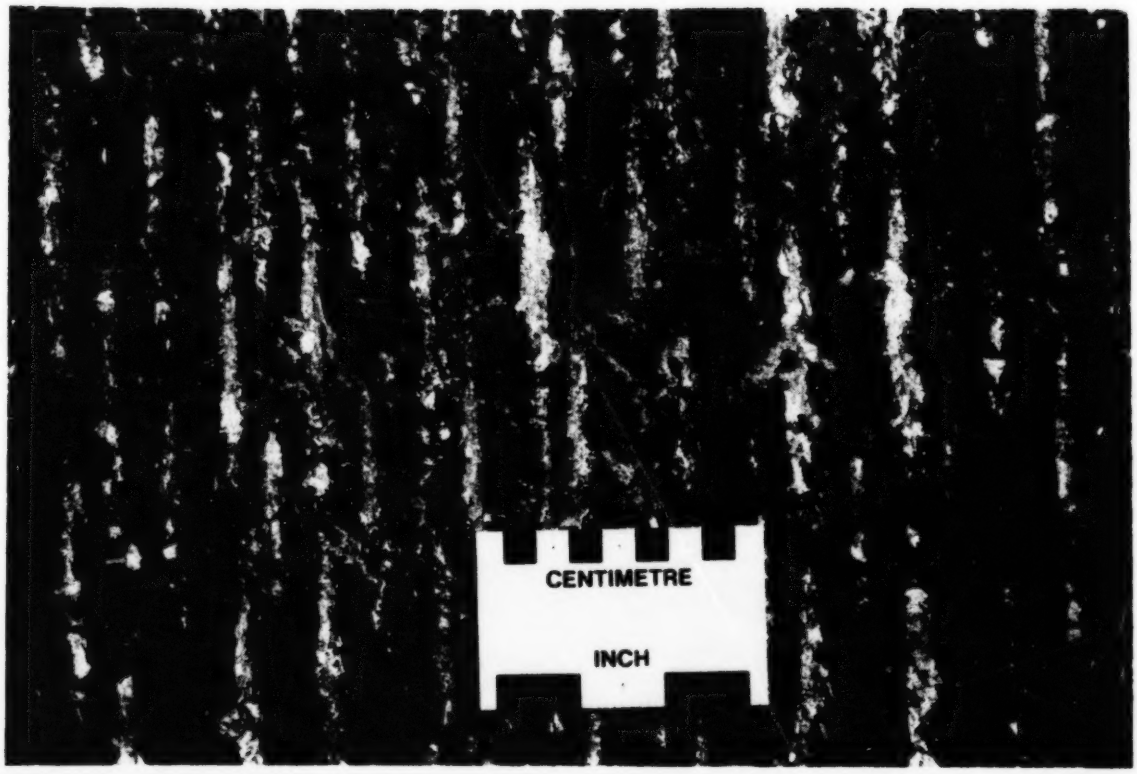


Figure 31: Appearance of pavement surface after milling.
Contract 79-23, Hwy. 41 north of Napanee.

Figure 32: Sakai (ER-160) milling machine on Contract 80-28, Hwy. 15/29 north of Smiths Falls.

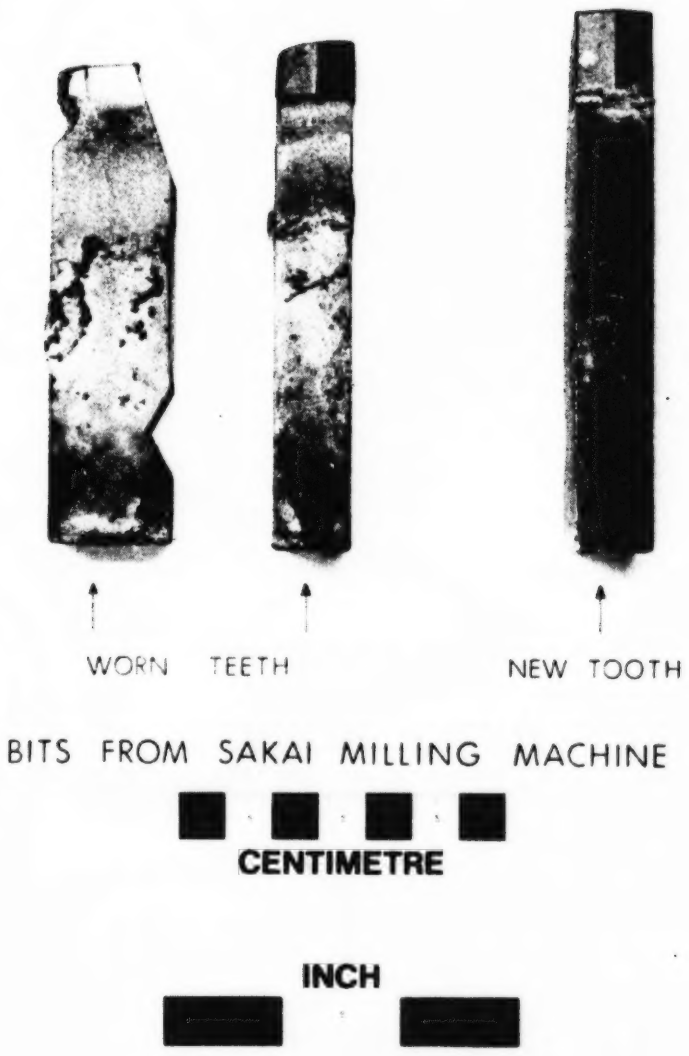


Figure 33: Note hard, tungsten carbide face on each tooth.

APPENDIX IV

TENTATIVE TEST METHOD FOR PETROGRAPHIC EXAMINATION OF ASPHALT CORE SAMPLES

memorandum

Ontario

To: Mr. J. B. MacMaster
Pavement and Foundation Design
Central Building, Downsview

Date: 1981 01 28

From: Geotechnical Section
Northwestern Region

RE: Information to Contractors
Bidding on Recycling Projects

Further to my letter of January 10, 1980 in which I explained the procedure of a proposed Petrographic Examination to evaluate and report to bidding contractors on the hardness of pavements to be milled, I now attach a slightly modified procedure. The previously mentioned 900 grams maximum amount to be tested has been decreased to an amount closer to the established P.N. The reason for this change was to decrease the amount of time required to perform this test while maintaining some degree of accuracy and reproducibility.

I also attach a form that we propose on using to record the results of the examination. The results will be shown in the contract documents along with the soils borings.

Any comments would be appreciated.

J. R. Girard
Head, Geotechnical Section

JRG/blr
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c.c. Heads of Geotechnical (all Regions)
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TENTATIVE:

Proposed Method for Petrographic Examination of Asphalt Core Samples from Planing Contracts.

PURPOSE:

To basically identify the harder aggregate types in the core sample.

METHOD AND PREPARATION:

The asphalt is to be extracted from the core as per M.T.C. Test Method LS 282 and the aggregate sieved to remove the pass No. 4 material. The petrographic examination is to be done on the material as obtained from LS 282 and sieving. A minimum of 400 grams of retained No. 4 material must be obtained from the core for the examination.

The material from sieving shall not be recombined but kept in three size fractions, i.e. retained 9.5 mm; pass 9.5 mm, retained 6.7 mm; pass 6.7 mm, retained 4.75 mm. A representative sample of oven dried aggregate shall be prepared to not exceed the following approximate masses.

Pass	Retain	Max. Mass, g
19.0 mm (3/4")	9.50 mm (3/8")	1,000
9.5 mm (3/8")	6.70 mm (No. 3)	200
6.7 mm (No. 3)	4.75 mm (No. 4)	75

CALCULATIONS:

When the test is performed on different size fractions, calculate a weighted average value.

REPORTING:

Identify the rock types of the aggregate that normally fall into Block I and Block II of the Coarse Aggregate Petrographic Analysis Form PR-CC 343 and report their weighted average percent of the total aggregate (core) sample. Report the aggregate that normally falls into Block III and Block IV as the weighted average percent of poor and deleterious aggregate of the total (core) sample.

NOTES:

After extracting and sieving, the aggregate may require an additional rinse in Tri 1:1:1 or alcohol and may require washing in soap and water to enable identification.

PETROGRAPHIC EXAMINATION - CORE

DATE _____

SAMPLE NO. _____

LOCATION OF SAMPLE _____

W.P. OR CONTRACT NO. _____

WORK LOCATION _____

MILITIA MAP NO. _____

ORIGINAL SOURCE _____

PIT LOCATION _____

		TYPE	%*
BLOCK I	GOOD AGGREGATES	CARBONATES (LIMESTONE & DOLOMITE)	
		SANDSTONE	
		GNEISS - SCHIST	
		QUARTZITE (COARSE & FINE GRAINED)	
		GREYWACKE - ARKOSE	
		VOLCANIC	
		GRANITE - DIORITE - GABBRO	
		TRAP	
BLOCK II	FAIR AGGREGATES	CARBONATES (LIMESTONE & DOLOMITE)	
		GNEISS - SCHIST	
		CHERT - CHERTY CARBONATES	
		GRANITE - DIORITE - GABBRO	
		VOLCANIC	
		ENCRUSTATION	
		ARGILLITE	
BLOCK III & IV		POOR AND DELETERIOUS AGGREGATES	

LABORATORY COMMENTS _____

NOTE * REPRESENTS THE % OF ROCK TYPE IN CORE SAMPLE

LOG NO. _____